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Gas-phase optical fiber photocatalytic reactors for indoor air application: a preliminary study on performance indicators

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Abstract. The development of advanced air cleaning technologies aims to reduce building energy consumption by reduction of outdoor air flow rates while keeping the indoor air quality at an acceptable level by air cleaning. Photocatalytic oxidation is an emerging technology for gas-phase air cleaning that can be applied in a standalone unit or a subsystem of a building mechanical ventilation system. Quantitative information on photocatalytic reactor performance is required to evaluate the technical and economic viability of the advanced air cleaning by PCO technology as an energy conservation measure in a building air conditioning system. Photocatalytic reactors applying optical fibers as light guide or photocatalyst coating support have been reported as an approach to address the current light utilization problems and thus, improve the overall efficiency. The aim of the paper is to present a preliminary evaluation on continuous flow optical fiber photocatalytic reactors based on performance indicators commonly applied for air cleaners. Based on experimental data, monolith-type optical fiber reactor performance surpasses annular-type optical fiber reactors in single-pass removal efficiency, clean air delivery rate and operating cost efficiency.

1. Introduction

In modern airtight buildings, mechanical ventilation has a major role in protecting the building occupant's health by supplying outdoor air to dilute the indoor air pollutant concentrations to levels that are safe for people. Although increased ventilation rates are related to reduction in negative health effects [1], higher airflow rates also result in increased energy consumption of building systems (heating, cooling, humidification, dehumidification) that condition the outdoor air [2] to achieve the required supply air thermal parameters. As the energy consumption of air-conditioning systems account for almost half of the total building energy consumption [3], there is an economic motivation to reduce the ventilation rate provided that indoor air quality requirements are met.

ASHRAE Standard 62.1 [4] describes an alternative method, Indoor Air Quality Procedure (IAQ procedure), for determining outdoor air quantities needed to achieve acceptable air quality. IAQ procedure allows the system designer to consider alternate indoor air pollution control strategies such as source control or air cleaning to achieve the same or improved IAQ at lower ventilation rates. While solutions for filtering particulate matter are mature, technologies for gas-phase air cleaning are in various development stages. Photocatalytic oxidation (PCO) is one of such emerging engineered controls for gaseous air pollution that involve a system of a light source, a photocatalyst material, a support structure for photocatalyst material and a reactor housing. Inside the photoreactor system, a series of light induced chemical reactions on the photocatalyst surface decompose organic pollutants into benign final products, such as water and carbon dioxide. There are a number of different reactor types that have been applied for gas-phase photocatalytic oxidation. Common laboratory plate and annular photoreactors are used to study kinetic parameters at low flow rates, but they are not suitable for practical air-conditioning applications where the residence times are much smaller due to high air face velocities in ducts and air-handling units. From the technical viewpoint, it can be stated that to have potential for commercialization, PCO reactors must allow high throughput at low pressure drop and an example of reactor type that has abilities to meet the requirements is monolith reactor [5].

Currently the vast majority of research focuses on performance enhancement of photocatalytic process, but practical application of PCO air cleaners to a large extent depend on the PCO device energy consumption in comparison with alternative air cleaning techniques [6]. If the energy consumption of PCO device is less than of ventilation to achieve the same removal rate of indoor air contaminants, then there is an economical interest in applying PCO air cleaning [7]. Presently, the analysis on PCO energy consumption in comparison to alternative solutions is limited, but the information is needed to facilitate the evaluation of the efficacy of the PCO technology for the applications in built environments. The determination of performance indices is beneficial for several reasons, which include simplified understanding of influencing factors, benchmarking alternative solutions and energy efficiency.

This paper presents the preliminary comparison of performance data of optical fiber PCO reactors. The main aim of the study is to theoretically evaluate contaminant decomposition and energy efficiency of continuous flow optical fiber photocatalytic reactors based on relevant experimental datasets published in peer-reviewed literature. The determination of performance indices is beneficial for several reasons which include simplified understanding of influencing factors, benchmarking alternative solutions and energy efficiency.

2. Methods

2.1. Database development

A database of experimental information on continuous flow photocatalytic reactors that use optical fibers as support or light guide was developed. Searches for relevant experimental studies were conducted in the following databases: Scopus, Web of Science and Google Scholar. Main keywords used in combination were optical fiber, photocatalysis, photocatalytic oxidation, air, gas. Further searches to find relevant sources in the databases were done by back-tracking and forward-tracking approach from the main sources. In addition, internal references in the main documents from initial search were followed up. Articles that discussed gas-phase photocatalytic oxidation by continuous flow reactors with artificial irradiation sources that utilize optical fibers in various configurations were considered relevant for this study. In total 13 papers with 17 datasets were included in the database. Information, both descriptive and numerical, on reactor-system setup description, reactor operational conditions and studied contaminant were extracted to a spreadsheet document.

2.2. PCO reactor performance analysis

The pollutant removal performance and energy performance of optical fiber reactors were evaluated by three indices that are commonly used for rating air cleaner devices. The indices were calculated based on data for the highest flow rate condition presented in the relevant articles.

Single-pass removal efficiency, also conversion, is a performance index that quantifies the rate of air contaminant removal in the air cleaning device as the air flows through. Single-pass efficiency can be calculated as follows:

$$\eta_i = \left(1 - \frac{C}{C_0}\right) \cdot 100\% \tag{1}$$

where η_i is the pollutant single-pass removal efficiency, C_0 is the initial concentration of pollutant entering the reactor (ppm or g/m^3) and C is the final concentration of pollutant leaving the reactor (ppm or g/m^3).

Clean air delivery rate (CADR) is a measure which characterizes the capacity of clean air delivered by an air cleaning device. It is important to note that "clean" refers to absence of target pollutants. This metric is useful for ranking different air cleaning methods and also for comparing the pollutant removal effectiveness of ventilation against air cleaning strategy [8]. CADR for single-pass gaseous contaminant removal can be computed as [9]:

$$CADR = \eta_i \cdot Q \cdot E \tag{2}$$

where η is the single-pass efficiency, Q is the air flow rate passing through the photocatalytic reactor (m^3/h) and E is a short-circuit factor. Under well-mixed conditions E equals 1.

Operating cost effectiveness [8], also called as energy efficiency index [10-12] is an index to quantify the energy performance of contaminant decomposition by PCO reactor and it can be used to rank different reactor configurations. Operating cost effectiveness can be found as follows [8]:

$$OCE = \frac{CADR}{P_c} \tag{3}$$

where OCE is the operating cost effectiveness ((L/min)/kW) and E_c is the electric power consumption of photocatalytic reactor (kW).

3. Results

Three performance indicators, single-pass removal efficiency, clean air delivery rate and operating cost efficiency, were indirectly found by calculation from published experimental datasets. The description of reactor setups, operational conditions and calculated values for performance indices are tabulated in Table 1. The higher the indicator values, the more efficient the reactor is.

In the vast majority of the studies, TiO_2 was used as the photocatalyst material and in only two studies doped TiO_2 catalysts were applied. The experiments were conducted mostly in room temperatures, relative humidity ranged from 0 to 50% in datasets relevant for this study. Air flow rates used were typically very low and not applicable for real mechanical ventilation applications. Artificial UV irradiation sources used in the reactor systems were research arc lamps, fluorescent black light tubes and mercury vapor lamps. In one study UV-LED was used as a light source. Reaction intermediates were detected in 7 articles [13; 14; 16; 17; 22; 23; 26]

Table 1. Optical fiber photocatalytic reactor performance indices.

Ref.	Type	Reactor description	Operating conditions	Pollutant	η, %	CADR, L/min	OCE, (L/min)/kW
[13]	A	140 TiO_2 coated OFs in cylindrical housing; 400 W HP Hg lamp (365 nm)	T=25˚C; RH=0; Q=0,5 L/min I=32,6 mW/cm^2	isopropanol; C_0=23,1 g/m^3; C=22,6 g/m^3	2,2	0,011	0,028
[13]	A	140 TiO_2 coated OFs in cylindrical housing; 400 W HP Hg lamp (365 nm)	T=25˚C; RH=15%; Q=0,5 L/min I=20,4 mW/cm^2	toluene; C_0=18,7 g/m^3; C=17,0 g/m^3	9,1	0,009	0,023
[14]	A	140 TiO_2 coated OFs in cylindrical housing; 400 W HP Hg lamp (365 nm)	T=20˚C; RH=0; Q=0,84 L/min I=32,6 mW/cm^2	tetrachloroethylene; C_0=13,3 g/m^3; C=7,9 g/m^3	40,8	0,343	0,859
[14]	A	140 TiO_2 coated OFs in cylindrical housing; 400 W HP Hg lamp (365 nm)	T=20˚C; RH=0; Q=0,61 L/min I=32,6 mW/cm^2	trichloroethylene; C_0=7,8 g/m^3; C=3,9 g/m^3	50	0,305	0,763

Table 1 continues.

[15]	A	4 TiO_2 coated OFs in cylindrical housing; 300 W Xe arc lamp (330 nm)	T=33˚C; RH=0; Q=4,75 mL/min	acetone; C_0=500 ppm; C=450 ppm	10	0,000	0,002
[16]	A	1 TiO_2 coated OF in cylindrical housing; 75 W Xe arc lamp (365 nm)	T=25˚C; RH=30%; Q=0,2 L/min I=271,6 mW/cm^2	benzene; C_0=10 ppm g/m^3; C=9,2 ppm	8	0,016	0,215
[17]	A	1 TiO_2 coated OF in cylindrical housing; 75 W Xe arc lamp (365 nm)	T=25˚C; RH=30%; Q=0,1 L/min I=210 mW/cm^2	benzene; C_0=10 ppm; C=7,5 ppm	25	0,025	0,333
[18]	A	1 TiO_2 coated OF in cylindrical housing; 75 W Xe arc lamp (365 nm)	T=25˚C; RH=15%; Q=0,3 L/min I=270 mW/cm^2	benzene; C_0=10 g/m^3; C=8,8 g/m^3	12	0,036	0,480
[18]	A	1 TiO_2 coated OF in cylindrical housing; 75 W Xe arc lamp (365 nm)	T=25˚C; RH=15%; Q=0,3 L/min I=270 mW/cm^2	isopropanol; C_0=10 g/m^3; C=7,5 g/m^3	25	0,075	1,000
[18]	A	1 TiO_2 coated OF in cylindrical housing; 75 W Xe arc lamp (365 nm)	T=25˚C; RH=15%; Q=0,3 L/min I=270 mW/cm^2	trichloroethylene; C_0=10 g/m^3; C=6,7 g/m^3	33	0,099	1,320
[19]	A	272 TiO_2 coated OFs in rectangular housing; 15 W BL lamp (365 nm)	T=25˚C; RH=10%; Q=0,1 L/min I=1,27 mW/cm^2	acetone; C_0=70 ppm; C=33,6 ppm	52	0,052	3,467
[20]	A	1 TiO_2 coated OF in cylindrical housing; 3 W UV-LED (365 nm)	T=25˚C; RH=40%; Q=0,1 L/min I=121,6 mW/cm^2	isopropanol; C_0=10,2 ppm; C=9,5 g/m^3	7	0,007	2,333
[21]	CR	1 OF with coated air channels inside; 200 W UV lamp	Dry conditions	ethylene; C_0=100 ppm; C=87 ppm	13	0,016	0,078
[22]	M	Mn/TiO_2 coated monolith channels with 196 OFs as light guide; 8 W LP Hg lamp (185+254 nm)	T=25˚C; RH=23%; Q=5,4 L/min I=2 mW/cm^2	m-xylene; C_0=207 ppb; C=103 ppb	50	2,700	337,500
[23]	M	TiO_s coated monolith channels with OFs as light guide; three 8 W UV-C lamps (254 nm)	T=25˚C; RH=50%; Q=1,6 L/min I=0,026 mW/cm^2	a-pinene; C_0=600 ppb; C=48 ppb	92	1,472	61,333
[24]	M	TiO_2 coated monolith channels with OFs as light guide; three 8 W UV-C lamps (254 nm)	T=25˚C; RH=50%; Q=1,6 L/min I=0,026 mW/cm^2	formaldehyde; C_0=1,1 ppm; C=0,088 ppm	92	1,472	61,333
[25]	M	Ag/TiO_2 coated monolith channels with 196 OFs as light guide; 8 W LP Hg lamp assumed (185+254 nm)	T=25˚C; Q=10,4 L/min I=7,5 mW/cm^2	isopropanol; C_0=160 ppb; C=57,9 ppb	63,8	6,649	831,075

A – annular reactor; CR – channeled optical fiber reactor; HP Hg lamp – high pressure mercury vapor lamp; I – irradiation; LP Hg lamp – low pressure mercury vapor lamp; M – monolith reactor; nm – nanometer (unit of wavelength); OF – optical fiber; RH – relative humidity; Xe arc lamp – xenon arc lamp; T – operating temperature; TiO_2 – titanium dioxide; UV LED – ultraviolet light emitting diode; UV-C lamp – ultraviolet lamp with primary wavelength at C-band

4. Discussion

Reported optical fiber photoreactor configurations can be divided between two main reactor types: annular reactors and monolith reactors. In annular reactors, optical fibers served both as a light guide and a photocatalyst support. In monolith reactor design, optical fibers were used only as a light guide to transmit light energy more uniformly into honeycomb-monolith channels. In one reported research, a combination of annular and monolith reactor was used in which optical fiber itself had air channels inside, therefore, the optical fiber was both a light guide and a support for catalyst. According to performance evaluation, monolith reactors with optical fibers are superior to annular reactor when comparing single-pass removal efficiencies, CADR values and operating cost efficiencies. Still, the CADR values of bench-scale reactors are much lower than the CADR values for air cleaners reported in the literature [9; 26].

Lower air flow rates result in longer retention times in reactor space that are more favorable for high single-pass removal efficiencies, but at the same time cause lower CADR values. For ventilation rate reduction, single-pass efficiency of around 20% has been found to be equivalent to 50% of reduction in typical US office building [27], therefore the goal should be to achieve optimal removal efficiencies at high air flow rates that are conventional for ventilation systems.

On the other hand, the single-pass removal efficiency and the CADR number cannot take into account the potential health risks, such as by-product generation. For that purpose, health-related index, which quantifies the possible negative health effects, could be calculated in addition to other performance indicators [28]. In this research the health-related index values were not found due to lack of information on removal process by-product concentrations.

Operating energy performance is affected by the light source power consumption. Thus, the lamp that can provide the same irradiation at lower electrical power consumption will contribute to higher operating cost efficiency value. Research arc lamps that are often used in bench-scale optical fiber PCO reactors are not relevant for practical applications. Currently, the UV tubes are the most optimal choice for artificial UV source, but the development of UV-LEDs, that can provide high enough irradiation, would significantly contribute to lowering PCO reactor operational costs.

5. Conclusion

The aim of this preliminary study was to analyze continuous flow photocatalytic reactors that utilize optical fibers as a support for photocatalyst or as a light guide to transmit UV irradiation more uniformly into the reactor space. The analysis was based on a theoretical approach of applying quantitative air cleaner performance indicators, single-pass removal efficiency, clean air delivery rate and operating cost effectiveness, to bench-scale laboratory PCO reactor setups reported in the literature.

Monolith-type optical fiber reactors had higher removal efficiencies and CADR values, although they operated at an order of magnitude higher air flow rates. In addition, monolith-type reactors were more energy efficient due to using low wattage UV lamps. Therefore, based on existing studies, it is more reasonable to use optical fibers as light guide, not as photocatalyst support.

For future research on the topic, it is recommended that different performance indices should be reported to make comparison between reactor configurations and also between alternative purification methods possible. As by-product generation is a current limitation of PCO technology, it is advisable to report the issue in PCO related experimental research, because then it is possible to take potential health risks into consideration. In the context of indoor air purification, the experimental data has more value if research on PCO reactor performance is done at operating conditions that are relevant to practical systems.

The research is ongoing to compare photocatalytic air cleaning to ventilation in removing gaseous air contaminants and also, to define functional requirements for PCO air cleaners to be technically and economically competitive alternative to ventilation.

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