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Antibacterial performance of a novel photocatalytic-coated cordierite foam for use in air cleaners

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\textbf{A B S T R A C T}

A novel titanium dioxide-coated cordierite foam (\textit{TiO}_2/cordierite foam) was developed for use in air cleaners. By a simple impregnation procedure, \textit{TiO}_2 nanoparticles were immobilized firmly onto the surface of a cordierite foam substrate through high-temperature (500 °C) calcination. The strong bactericidal performance of the fabricated foam was evaluated by a newly developed test method for complex three-dimensional through-pore structures. This method could trace 5–6 log units of decrease in bacterial cell numbers in an air environment, thus meeting the criteria of both the JIS and ISO standard test methods. With 0.25 mW cm\(^{-2}\) of UV-A irradiation for 24 h, the bactericidal rate of the \textit{TiO}_2/cordierite foam exceeded 99.9% for five types of airborne or droplet-based infectious pathogens: \textit{Escherichia coli} (\textit{E. coli}), \textit{Pseudomonas aeruginosa} (\textit{P. aeruginosa}), \textit{Legionella pneumophila} (\textit{L. pneumophila}), \textit{Klebsiella pneumoniae} (\textit{K. pneumoniae}), and methicillin-resistant \textit{Staphylococcus aureus} (MRSA). The results of repeat testing, where the same sample was used three times, revealed that the bactericidal rate for \textit{E. coli} was maintained at 99.9% in the second and third use, indicating that the \textit{TiO}_2/cordierite foam possesses a long-term bactericidal action. The \textit{TiO}_2/cordierite foam also exhibited a high photocatalytic degradation capability on gaseous acetaldehyde, which is associated with sick building syndrome, and volatile organic compounds to generate \textit{CO}_2 and H\textsubscript{2}O. The results demonstrated that \textit{TiO}_2-coated cordierite foam has great potential for use in air-cleaning filters with not only high bactericidal performance to remove pathogens in the air and in droplets, but also strong decontaminating and deodorizing functionality.

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1. Introduction

During the past decade, airborne diseases, such as severe acute respiratory syndrome (SARS), which first broke out in China in 2003 [1], and the epidemic of influenza which spread globally in 2009 [2,3], have seriously threatened human health. Simultaneously, bacteria from clinical and non-clinical settings have been becoming increasingly resistant to conventional antibiotics. Especially, the report about New Delhi metallo-\beta-lactamase 1 (NDM-1), a new “resistance gene”, published by Kumarasamy et al. in 2010 [4] caused an unprecedented world-wide panic. Therefore, the development of breakthrough antimicrobial methodologies including medical drugs, fungicides and bactericidal materials, is becoming a central concern in many scientific fields.

Recently, titanium dioxide (\textit{TiO}_2) has attracted widespread attention as an antimicrobial semiconductor photocatalyst because it is regarded as environmentally friendly, while at the same time possessing strong bactericidal properties. This activity is associated with the strong oxidizing power of \textit{TiO}_2 when it is exposed to UV light with wavelengths of less than 385 nm. When exposed to near-UV light, \textit{TiO}_2 can generate a hole-excited electron pair due to band gap excitation on its surface [5]. Through the combined action of superoxide radicals (\textit{O}_2\textsuperscript{−}) produced by the reduction of oxygen with an excited electron, hydroxyl radicals (\textit{OH}\textsuperscript{•}) produced by the oxidation of water and photo-generated electrons/holes, most organic compounds can be decomposed and mineralized to \textit{CO}_2 and H\textsubscript{2}O [6–9]. As the single most important effect of \textit{TiO}_2 photocatalysis, its bactericidal activity has been studied in various microorganisms including \textit{Escherichia coli}, \textit{Pseudomonas aeruginosa}, and \textit{Staphylococcus aureus} (\textit{S. aureus}), as well as in fungi. In addition, the mechanism of this antimicrobial photocatalysis has been
revealed as the loss of cell membrane integrity caused by electrons/holes or by reactive oxygen species (ROS) [10–12]. While photocatalysis for water and air purification has been scientifically studied for more than two decades, and the bactericidal activity of TiO₂ photocatalysts is thus well known, in-depth studies of selective applications of TiO₂ photocatalysts are still required. Although a familiar nano-material, TiO₂ nano-particles have been found to be difficult to separate and regenerate after use in practical systems, thus limiting the commercialization of TiO₂. Therefore, many methods of immobilizing TiO₂ nano-particles onto different substrate materials have been tested; these include magnets [13], chemical vapor deposition [14], and sol–gel processes [15]. Typically, TiO₂-coated medical devices and equipment such as catheters [10,16], lancets [17] and surgical masks [18] have been developed with a view to self-sterilization functionality to aid in the reduction of nosocomial infections. Highly porous ceramic foams including porous alumina [19], porous silica [20], activated carbon [21], as well as nickel foam [22], have been chosen as substrates for photocatalytic water and air purification and disinfection systems. Although numerous studies have proposed different application modes for photocatalyst-immobilized porous materials, further technological breakthroughs to realize higher-quality products are required for high-grade practical applications.

Additionally, with the commercialization of TiO₂ photocatalysts, reliable methods of assessing the bactericidal properties of a range of photocatalytic products have become essential to ensure product quality. The standard test methods to evaluate the antibacterial activity of TiO₂ photocatalyst-coated flat samples under UV-A light were established by the Japan Institute of Standards (JIS) in 2006 [JIS R 1702] [23] and the International Organization for Standardization (ISO) in 2009 [ISO 27447] [24]. However, for photocatalyst-coated porous materials, no appropriate assessment method has so far been available.

The present study had two objectives. The main objective was to develop a novel air-cleaner filter by coating ceramic (cordierite) foam with TiO₂ and evaluate its bactericidal activity using gram-negative E. coli, P. aeruginosa, Legionella pneumophila, Klebsiella pneumoniae, and gram-positive MRSA. The second objective was to develop a reliable test method, involving a simulation of the actual usage of the fabricated foam, in order to accurately assess the bactericidal performance of the product. Also, because the TiO₂-coated cordierite foam was developed for air-cleaner filters, the decomposition performance of the foam on harmful gases was examined by using gaseous acetaldehyde, which is associated with sick building syndrome, and volatile organic compound (VOC) pollutants.

2. Materials and methods

2.1. Preparation of TiO₂-coated ceramic foam

The surface of a cordierite foam substrate was coated with TiO₂ by a simple impregnation procedure. Pieces of the commercially available cordierite foam (2MgO/2Al₂O₃/5SiO₃) with 80–88% porosity were cut to 23 mm × 23 mm × 10 mm and were immersed in a TiO₂ slurry supplied by Showa Titanium Co. Ltd. (Toyama, Japan). The slurry was composed of 15 wt% TiO₂ nano-particles (anatase phase; over 90%) with 80–100 m² g⁻¹ of specific surface area, and distilled water. After removing the residual solution from the holes in the foam, it was calcined under experimental conditions of 500 °C for 4 h to provide greater mechanical strength in the coating film. The crystalline structure of TiO₂ was examined by X-ray diffractometry (XRD; RINT 1500, Rigaku).

2.2. Preparation of bacterial suspensions

The E. coli (NBRC 3972) and K. pneumoniae (NBRC 13277) used in this study were obtained from the Biological Resource Center of the National Institute of Technology and Evaluation (NITE-BRC, Tokyo, Japan); the P. aeruginosa (IID 1700) was provided by the Institute of Medical Science, University of Tokyo (Tokyo, Japan); and the L. pneumophila (CTC/GIFU 00296) was purchased from the Department of Microbiology, Regeneration and Advanced Medical Science, Graduate School of Medicine, Gifu University (Gifu, Japan). The MRSA (N315) was donated by the Department of Microbiology, Graduate School of Medicine, Juntendo University (Tokyo, Japan).

E. coli, P. aeruginosa, K. pneumoniae and MRSA were cultivated twice consecutively on nutrient broth agar (NA) plates (Becton, Dickinson and Company, Franklin Lakes, NJ, USA) at 37 °C for 18–20 h. Subsequently, the live cells were suspended in 1/500 nutrient broth solutions which contained 6 mg of meat extract, 20 mg of peptone, and 10 mg of NaCl per liter at pH 7.0, and then diluted to approximately 10⁷ colony-forming units (CFU) per ml. L. pneumophila suspensions were prepared following a similar method, except that L. pneumophila was pre-cultured with a charcoal yeast extract medium containing alpha-ketoglutarate (Becton, Dickinson and Company) at 37 °C for 72 h. These bacterial suspensions were used in the bactericidal tests for the TiO₂/cordierite foam, as described below. All of the reagents and concentrations used were prepared in accordance with the JIS R 1702 standard method.

2.3. Assessment of bactericidal effect of TiO₂-coated cordierite foam

The photocatalytic bactericidal effect of TiO₂/cordierite foam was investigated by an originally developed test method (Fig. 1), designed in consideration of the practical usage of the foam in air cleaners. The foam samples were soaked in the bacterial suspensions under optimal conditions for adsorption equilibrium to absorb a sufficient amount of bacterial cells on their surface. They were then treated to a “semi-dry” status by a centrifugal action, and were irradiated with UV-A light (FL20S Black Light Blue (BLB); λ = 352–368 nm; Toshiba, Japan) at 0.25 mW cm⁻² of light intensity, or were placed in the dark at a fixed room temperature of 26 °C. Illumination conditions of 0.25 mW cm⁻² were selected, in accordance with the JIS R 1702 standard method, because this is the maximum UV-A intensity that does not affect the growth of E. coli. The UV-A intensity was analyzed by an integrating actinometer for photocatalysis (C5936-01/H9958; Hamamatsu Photonics Co. Ltd., Hamamatsu, Japan). After illumination, the foam samples were removed into 50-mL centrifuge tubes containing 20 mL of PBS Tween-20 solution, and were then washed by intense vortex for 2 min to collect the bacterial cells on the foam surface. The viable bacterial cells in the washing solutions were detected by the colony formation method. Bare cordierite foam was used as a control. The bactericidal tests were repeated a minimum of three times for each bacterial strain to ensure the accuracy of the data. The regional variation and mean data are presented in the resulting diagrams.

The optimal conditions for the adsorption equilibrium of bacterial cells onto the TiO₂/cordierite foam mentioned above were investigated before commencing the formal assessment tests with a similar experimental procedure except for UV-A irradiation. The variables examined were the time for soaking the foam in the bacterial suspensions, the centrifugation speed, and the time required for the foam to reach “semi-dry” status. The washing time for “semi-dry” foam was also investigated in order to obtain a high recovery rate for the bacterial cells adsorbed by the foam. Three parallel tests
were performed in every investigation, and every test was repeated at least three times to ensure the accuracy of the results.

2.4. Evaluation of the decomposition performance on volatile organic compounds

The photocatalytic decomposition performance of TiO₂/cordierite foam was evaluated by the degradation of gaseous acetaldehyde in accordance with JIS 1701–2 [25], one of the standard methods for testing air purification performance. The test was carried out in a 500-ml sealed acrylic container by monitoring the concentrations of acetaldehyde and CO₂, a decomposition product, under UV light illumination. The foam sample was put into the sealed container, and then 5 ml of standard acetaldehyde gas (1%, balanced by N₂; Sumitomo Seika Chemicals Co. Ltd., Osaka, Japan) was injected into the container. By adsorption onto the foam, the acetaldehyde in the container decreased by approximately 30 ppmv (parts per million by volume) before UV illumination. The oxidative reaction of the gaseous acetaldehyde was implemented by a UV-LED lamp (NCUS003A(T)λ₃65 = 365 nm; Nichia, Tokushima, Japan) illuminating the foam sample at 50 mW cm⁻² of light intensity through a quartz window. The illumination was initiated when the adsorption equilibrium of gaseous acetaldehyde onto the foam was reached. Meanwhile, gas concentrations were monitored by using an Innova photo-acoustic field gas monitor (Model 1412; Innova Air Tech Instruments, Denmark). Bare cordierite foam was used for the control.

3. Results and discussion

3.1. TiO₂-coated ceramic foam

Ceramic foam possesses complex three-dimensional through-pore structures. This complex structure is thought to provide a large surface area to immobilize large amounts of TiO₂ photocatalyst. In the present study, TiO₂ nano-particles were firmly immobilized by high-temperature (500 °C) calcination onto the structural surface of the cordierite foam. The XRD patterns of cordierite foam before and after loading and sintering TiO₂ are shown in Fig. 2a and b. The difference plot between the Fig. 2a and b is shown in Fig. 2c. In these patterns, the diffraction peaks of crystalline TiO₂ are clearly detected, presenting that by calcination at 500 °C, TiO₂ coated onto the cordierite foam was crystallized into most anatase phase and a small part of rutile phase.

The surface morphology of the TiO₂ layer on the cordierite foam surface was investigated by scanning electron microscopy (SEM). The optical layer consisted of small TiO₂ platelets with smooth surfaces exhibiting a roughly average thickness of 10–20 μm, separated by deep cracks [Fig. 3(a–c)]. The cracks may have formed during or after the heat treatment due to the difference in heat dissipation between the cordierite substrate and the TiO₂ coating. These multiple microscopic cracks were expected to relieve the stress when the coated foams were struck. By comparison, bare cordierite foam exhibits a rough surface with many microscopic pores, as shown in Fig. 3(d–f). We considered that these microscopic pores might enhance the adhesive strength of the TiO₂ coating layer onto the bare cordierite foam. Up to now, a large number of papers on TiO₂ photocatalytic reactions have stressed that photocatalytic activity depends on the dose of TiO₂, the UV light intensity for irradiation, and the irradiation time. Yu et al. verified that photocatalytic efficiency strongly depends on the surface structure of the TiO₂ thin films prepared by the sol–gel method [26]. They proposed that the aggregation and growth of TiO₂ particles in the interior region of thick films which undergo long-term heat treatment leads to a decrease in the number of active surface sites. Thus, improving the crystalline mesoparticles of TiO₂ on the cordierite foam frame serves to increase its bactericidal activity and the purification performance of air-cleaning filters.
3.2. Bactericidal test method for TiO₂/cordierite foam and bactericidal activity assessment

Since the existing standard bactericidal test methods (JIS R 1702 and ISO 27447) were specifically established for two-dimensional photocatalytic surfaces, an appropriate bactericidal test method is needed for three-dimensional porous structures, such as TiO₂/cordierite foam. The method should be based on three considerations: (1) in line with the standard methods, the initial concentration of the bacterial cells attached to the photocatalytic surface of the samples should be no less than 10⁵–10⁶ CFU, which can trace 5–6 log units of decrease in bacterial cells; (2) the coated foam should be able to be used in air cleaner filters whose operational status is different from water treatment usage; (3) the obtained experimental data should be as reliable and stable as possible. Although these criteria can be satisfied easily with two-dimensional flat samples, it is difficult to fulfill them in the case of the random three-dimensional porous structures seen in ceramic foams.

For consideration (1), a very simple operation is used to flat samples in accordance with standard methods: pipette 100 µl of the bacterial suspension (approximately 10⁵ CFUs) onto the samples surface, and cover an adhesive film on the dripped suspension to spread it to attach the bacteria to the photocatalytic coating. However, this manner is impossible for porous foams. In order to ensure a high initial concentration of bacterial cells, we soaked the foam samples in the *E. coli* suspensions at a cell concentration of 10⁷ CFU ml⁻¹ for various periods of time. We then centrifuged the draped foam to remove the residual bacterial suspensions filling the holes in the foam in order to ensure that the photocatalytic surface was accessible to the bacterial cells being tested. Here, we investigated the optimum conditions, including the soaking time for adsorption equilibrium, the centrifugation speed and the time required to obtain “semi-dry” ceramic foam loaded with a sufficient number of evenly absorbed bacterial cells.

Fig. 4(A) shows that, when the centrifugation was performed for only 5 s at 3000 rpm, the number of bacterial cells loaded on the coated and bare foams did not meet the requirements of the standard methods. However, at 500 rpm, the residual bacterial suspensions filling the pores of the foam were completely removed; meanwhile, the number of adsorbed bacterial cells reached 10⁵ CFU. Fig. 4(B) shows that when the centrifugation speed was set at 500 rpm, centrifugation times in the range of 5–60 s did not significantly affect the number of viable bacterial cells adsorbed. Foam samples soaked in *E. coli* suspensions for 20 min were used in this investigation to enable adequate bacterial attachment to the foam.

We explain these data as follows: because the isoelectric point of TiO₂ is 6.1, its surface picks up tens of millivolts of negative charge when it is placed in deionized water at pH 7.0. This characteristic does not fundamentally change in a 1/500 NB solution which contains a small amount of organic matter and NaCl. In 1999,
Janusz et al. reported a surface measurement of about −11 mV for TiO$_2$ in a very low-concentration NaCl solution [27]. Meanwhile, bacterial cells also have a negative surface potential in conditions with a pH value over 4. Therefore, it can be inferred that bacterial cells may not be strongly adsorbed onto a TiO$_2$ thin film covering a cordierite foam frame in a neutral pH environment without UV-A irradiation. The thus adsorbed bacteria actually consist of microorganisms contained in a physically adsorbed 1/500 NB aqueous film. We estimated that the amount of adsorbed *E. coli* on the surface of the “semi-dry” foam depends on the thickness of the liquid film covering the foam frame. This phenomenon is similar to the film formation achieved with the spin coating method described by Brinker et al. in 1990 [28]: that is, the thickness of the liquid film is determined mainly by centrifugation speed, centrifugation time and the viscosity of the liquid while the initial liquid amount remains constant. The description is defined with the following well-known equation:

$$n = \frac{h_0}{\sqrt{1 + \left(4\rho_0 \rho T \eta^2 \right)}}$$  \hspace{1cm} (1)

where “$h$” is the liquid thickness; “$h_0$” is the initial liquid thickness (amount); “$\rho$” is the density of liquid; “$\omega$” is the revolution speed; “$T$” is time and “$\eta$” is dynamic viscosity. However, when the liquid density and viscosity, as well as the centrifugation time are extremely small, such as a 1/500 NB solution and 60 s, the centrifugation speed plays a decisive role. Obviously, the complete removal of the residual bacterial suspensions filling the holes of the foam and the loading of a sufficient amount of bacterial cells with high reproducibility onto the foam frame are the most important points for the effectiveness of the antimicrobial testing by the methods developed here. The liquid film covering the foam frame is equivalent to the bacterial suspension layer on flat samples prepared in accordance with the standard methods (JIS R 1702 and ISO 27447). In order to obtain reproducible data, we established 500 rpm and 30 s as the optimum centrifugal conditions in all the formal bactericidal tests described in this paper.

After the appropriate centrifugation conditions were established, the soaking time required to achieve adsorption equilibrium of *E. coli* suspensions onto the foam was examined in the range of 2−30 min. As shown in Fig. 4(C), after only 2 min of soaking, the bacterial cells were rapidly adsorbed onto the coated and bare foam, and reached ~2 × 10$^6$ CFU. Additionally, no obvious difference in the numbers of adsorbed *E. coli* cells was observed with soaking in the range of 2−30 min. The results revealed that TiO$_2$/cordierite foam possesses a high hydrophilicity, leading to almost immediate adsorption equilibrium. The results also demonstrated that the number of adsorbed *E. coli* cells was dependent on the thickness of the liquid covering the coated foam frame as described above. To ensure the stability of *E. coli* adsorption, we set the optimum soaking time at 10 min for all of the bactericidal performance evaluations described below.

Also, the washing time for collecting the bacterial cells adsorbed on the foam was examined in order to obtain stable and convincing experimental data. Because a PBS buffer with 0.7, w/v (%), of Tween-20 added was used as the washing solution, the collection rate of the adsorbed bacterial cells exceeded 90% after only 1 min of intense vortex. To stabilize the collection rate of *E. coli*, we set the optimum washing time at 2 min in all future bactericidal tests.

In order to confirm the applicability of the coated foam for air cleaner filters, we examined its photocatalytic bactericidal effects by temporal evolution for viable bacterial cells during UV irradiation; this required the irradiation of the “semi-dry” foam under a blacklight blue lamp in an “air environment” as shown in Fig. 1, and separate samples were taken at each sampling time point. To examine the temporal evolution precisely, the photocatalytic samples must be as identical as possible to each other, and also the number of viable cells loaded onto the samples should be almost the same for all samples. All of the data presented here indicate that the method we developed can load a sufficient number of bacterial cells, with high reproducibility and only ± 10% margin of error, thus enabling an effective examination of the photocatalytic bactericidal effects of TiO$_2$−coated cordierite foam. The remarkable difference between the standard methods and the newly developed method is the way of loading bacterial cells onto the TiO$_2$ coating. It is also a key point for obtaining accurate and reproducible experimental data.

The high bactericidal activity of the TiO$_2$/cordierite foam was confirmed for *E. coli*, *P. aeruginosa*, *L. pneumophila*, *K. pneumoniae* and MRSA, because these are the major pathogens associated with nosocomial infections. Fig. 5 shows the time−dependent decrease in the survival rate of the bacteria tested. With 0.25 mW cm$^{-2}$ intensity of UV−A irradiation for 24 h, the bactericidal rate of the TiO$_2$/cordierite foam exceeded 99.9% for all of the bacterial strains tested. No significant antibacterial effect was obtained when these bacterial strains were tested in the dark. Based on the above explanation of the adsorbed bacterial cells, the photocatalytic eradication of the bacterial cells contained in the liquid films covering the foam frame can be attributed to the reactive oxygen species (ROS) generated by photocatalysis. While the water on the foam surface deriving from water vapor via physisorption in an air environment is estimated to be lower than in artificial liquid films, there is no doubt that the bactericidal action of the TiO$_2$/cordierite foam can be mainly attributed to the reduction/oxidation of the adsorbed reactants directly by electrons/holes in the foam.

It can be seen in Fig. 5 that the survival of each strain of bacteria tested declined slightly on bare cordierite foam under UV−A irradiation. As is well known, UV−A wavelengths are less effective in inducing DNA damage related to bacterial death, because they are not absorbed by native DNA; however, they can still produce secondary photoreactions with existing DNA photoproducts or damage DNA via indirect photosensitizing reactions [29,30]. However, this decrease in survival cannot be identified as efficacious bactericidal action by JIS or ISO standards. In addition, it also has been noted that damaged DNA can be repaired by some bacteria (e.g. *E. coli*) in both light and dark environments, by mechanisms commonly referred to as photoreactivation and dark repair [31−33]. Photocatalysis has been demonstrated to inhibit the repairs attributed to the loss of cell membrane integrity caused by the electrons/holes or by reactive oxygen species (ROS) and the leakage of cell contents [12,34], highlighting the advantage of the application of TiO$_2$/cordierite foam in air disinfection.

Because the colony-forming method has a limitation in terms of detection, we immersed the foam loaded with *E. coli* cells and exposed to UV−A for 24 or 48 h in NB liquids in order to check whether or not bacteria adsorbed on the TiO$_2$/cordierite foam could be completely killed by UV−A irradiation. We then incubated them at 37°C for 24 h. During the incubation, we traced the OD$_{600}$ value to observe the growth of the surviving bacteria cells. According to the results shown in Table 1, the adsorbed bacteria cells were completely inactivated after 48 h of UV−A irradiation, even though the foam was 10 mm thick. This phenomenon can be attributed to the random refraction of UV−A by the TiO$_2$/cordierite foam.

Fig. 6 shows the results of the bactericidal tests when the same sample was used three times. As is seen from the data, the bactericidal activity decreased slightly with the second and third use. However, this reduction was only observed with 4 or 8 h of UV−A illumination. After 24 h of UV−A illumination, the bactericidal rates were maintained at 99.9% for the second and third use.
This indicates that the TiO₂/cordierite foam possesses a long-term bactericidal action and reusability. In an aqueous phase, dead or damaged bacterial cells can be washed off the active photocatalytic surface. However, in an air-phase system, the dead cells may have the potential to accumulate and block the photoactive surface. Jacoby et al. observed the mineralization of E. coli cell masses on a TiO₂ surface in air with long-term (75 h) UV-A illumination [35]. Therefore, the long-term bactericidal action and reusability of TiO₂ coated foam are beneficial in reducing active surface blocking.

### Table 1

| Shaking time (h) | Photocatalytic treatment for foam (h) | Bare cordierite foam | TiO₂/cordierite foam |
|-----------------|------------------------------------|---------------------|---------------------|
|                 |                                    | 24                  | 48                  |
| 0               |                                    | 0                   | 0                   |
| 4               |                                    | 0.12                | 0.01                |
| 6               |                                    | 0.70                | 0.06                |
| 8               |                                    | 1.12                | 1.17                |
| 24              |                                    | 2.18                | 1.97                | 1.81                |

* The TiO₂-coated and bare cordierite foam loaded with 10⁶ CFU of E. coli was treated by 0.25 mW cm⁻² of UV-A illumination for 24 and 48 h. Then, the foam was immersed in 20 ml of nutrient broth and was shaken in 37 °C for 24 h.

### 3.3. Decomposition performance of TiO₂/cordierite foam on gaseous acetaldehyde

In addition to its antibacterial properties, another important property of TiO₂/cordierite foam as an air cleaner is its ability to...
decontaminate and deodorize indoor air. This decontaminating and deodorizing ability was investigated by TiO₂ photocatalytic degradation on gaseous organic substrates, as described earlier. The reaction time profiles shown in Fig. 7A indicates that acetaldehyde concentration on TiO₂/cordierite foam decreases rapidly, while a simultaneous formation of CO₂ is observed. There is no decrease in acetaldehyde levels on the cordierite foam without TiO₂ loading, as shown in Fig. 7B. The decomposition rate constant for gaseous acetaldehyde – that is, k₂ = 15.6 (h⁻¹) – was calculated to be in the range of 0–0.15 h. The complete oxidation reaction of acetaldehyde (CH₃CHO) into CO₂ and H₂O shows that the smoother surface of the foam created in this experiment provides a higher photocatalytic reaction rate. This is very important from the viewpoint of practical applications, because it is known to be one of the principal odor-causing gases in indoor air, particularly in cigarette smoke [36].

4. Conclusion

A TiO₂ film with highly crystalline mesoparticles was synthesized on the rough surface of a ceramic (cordierite) by a simple impregnation and calcination procedure. The smooth surface of the novel foam offered strongly photocatalytic bactericidal activity and decomposition performance. When treated by relatively low-intensity UV-A irradiation (0.25 mW cm⁻²) for 24 h, the TiO₂-coated cordierite foam reduced by over 99.9% the number of viable cells of three gram-negative strains of bacteria (E. coli, L. pneumophila, K. pneumoniae), and also the gram-positive methicillin-resistant S. aureus, all of which are extremely important airborne infectious bacteria. The bactericidal activity assessment was carried out by an original test method developed for the three-dimensional porous structures seen in various ceramic and metal foams. All of the data obtained in this study showed high reproducibility and indicated that the bactericidal test method developed here can trace 5–6 log units of decrease in bacterial cells in environmental air and can thus meet the criteria of the JIS and ISO standard test methods. The novel foam also exhibited a high photocatalytic degradation reaction on gaseous acetaldehyde to generate CO₂ and H₂O. All of these results indicate that TiO₂-coated cordierite foam is a promising material for use in air-cleaning filters by virtue of its high bactericidal activity and decontaminating, deodorizing performance for air disinfection and purification.

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