

# Ozone deposition velocities on cotton clothing surface determined by the field and laboratory emission cell

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## Abstract

Interfacial ozone-initiated chemistry can greatly influence human exposure to reactants and products in the indoor environment. As the nearest reaction interface to human body, clothing assumes an important role in the generation of ultrafine particles and volatile organic compounds when reacting with indoor ozone. However, little is known about the kinetics of ozone-clothing reactions. This investigation developed a convenient method to examine the reaction kinetic parameters of ozone-clothing reactions by using a field and laboratory emission cell. Deposition velocity can be determined in a short period by this method. The study found that the deposition velocity and reaction rate constant for ozone-cotton vest reactions were not significantly affected by the ozone concentration, air flow velocity and long soiling duration (>6 h) of the vest. However, whether or not the vest had been soiled with skin oil is key to the magnitude of the deposition velocity and reaction rate constant. The ozone deposition velocities on soiled cotton vest surface are approximately constant under typical indoor conditions. The deposition velocity and reaction rate constant of ozone-initiated reactions with soiled cotton vest are  $0.79 \pm 0.17$  and  $2.43 \pm 0.71$  cm/s, respectively, at room temperature.

## Keywords

Indoor ozone chemistry, Deposition velocity, Reaction rate constant, Clothing, Mass transfer

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## Introduction

Over the past decade, the outdoor ozone concentration in China has risen significantly.<sup>1</sup> Observations at three sites in Beijing showed that the annual average concentration of ozone was up to 42.1 ppbv in 2008,<sup>2</sup> while a maximum hourly average ozone concentration of 286 ppbv was recorded in northern China in 2005.<sup>3</sup> Wang et al.<sup>4</sup> estimated that China's annual mean surface ozone level in 2050 would increase by 8.7 ppbv compared with the level in 2000. This is almost twice the expected mean global change of 4.6 ppbv. Outdoor ozone is transported to indoor spaces such as homes and offices mainly by ventilation and infiltration.<sup>5,6</sup> Hence, the indoor ozone level increases with increasing outdoor ozone levels.

Indoor ozone has been reported to have the ability to enhance the products of ozone-initiated reactions.<sup>7</sup> Ozone and its reaction products can be detrimental to human health. Ozone could have a negative effect on pulmonary function<sup>8</sup> and cardiovascular function.<sup>9</sup> Even at low concentration, ozone is associated with an increased risk of premature mortality.<sup>10</sup>

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Furthermore, ozone, as a major driver of indoor chemistry, can react with various organic compounds in gas phase and on surfaces. Products from indoor ozone-initiated reactions (e.g. formaldehyde, acrolein, fine and ultrafine particles) are either known to affect, or have been suspected of causing adverse, human health.<sup>11</sup> In many cases, ozone surface reactions have a greater influence than gas-phase reactions on human chemical exposure.<sup>12</sup> Owing to the presence of unsaturated organic species in or on the surface, many indoor materials, including latex paint,<sup>13</sup> flooring materials,<sup>14</sup> carpet,<sup>15,16</sup> wooden panels,<sup>17</sup> heating, ventilation and air conditioning (HVAC) materials,<sup>18</sup> can react with and consume ozone. Humans are also regarded as an important sink for ozone because ozone can react with skin oils,<sup>19</sup> hair<sup>20</sup> and clothing.<sup>21</sup>

Weschler et al.<sup>22</sup> reported that the presence of occupants had a significant effect on indoor ozone consumption. In a specific aircraft cabin, it was found that over 55% of the ozone was removed by the occupants and their clothing. Other studies have found that the average 'per person' ozone deposition velocity ranged from 0.40 to 0.62 cm/s in a simulated office<sup>23</sup> and 0.20 to 0.23 cm/s in an aircraft cabin.<sup>24</sup> As the major covering of human body, clothing is one of the major reaction surfaces for indoor ozone reactions. The influence of ozone-clothing reactions on human health is enhanced since byproducts emitted from ozone-clothing reactions can directly move into the breathing zone of a human person. Wisthaler et al.<sup>25</sup> initially found that the ozone consumption was much higher when T-shirts were present. Later, Tamas et al.<sup>24</sup> reported that the ozone deposition velocity for a soiled T-shirt is about 0.19 to 0.27 cm/s. Rai et al.<sup>21</sup> obtained similar results, from 0.15 to 0.29 cm/s for soiled cotton T-shirts, and Coleman et al.<sup>26</sup> reported about 0.41 cm/s for soiled cotton clothing fabric.

However, the reaction conditions in previous investigations varied greatly across different experiments. Some major reaction conditions, including air flow velocity, were also uncontrollable in the chamber and office tests. As a result, the measured deposition velocities in the different studies are not comparable. Thus, the reaction kinetic constants (i.e. reaction rate constant) should be measured in order to extend the measured results into real indoor environment.

The objective of this investigation was to establish a reliable method to determine the ozone deposition velocity and reaction kinetic constants of ozone-clothing reactions using the field and laboratory emission cell (FLEC). Experiments to determine the effects of various factors such as ozone concentration, air flow velocity and the level of skin-oil-soiled clothing on reaction kinetic constants were performed.

## Materials and methods

### Materials

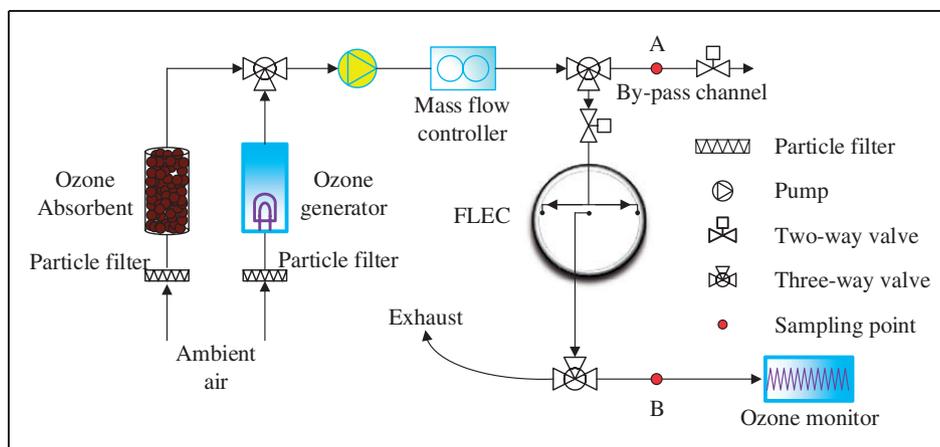
Cotton vests purchased from a local retail store were used to investigate the ozone-clothing reactions. The garments were from the same lot. The test specimens used as the reaction surfaces in all experiments were cut from the chest. All vests were first machine washed with a fragrance-free detergent (Babyganics, USA). To obtain soiled vests, a male student was asked to wear the vest and conduct normal daily activities (sleeping, attending classes, etc.) according to specified soiling durations. The vests to be tested were stored separately in clean aluminium-foil bags before the experiment. The storage duration was usually less than 12 h. The vest was cut into specimens before the experiment. The test specimens were placed in the FLEC with the exterior side of the test specimen being exposed to ozone during the experiment.

A ring of 0.15 mm thick Teflon film was placed on top of the test specimen to control the reaction area in order to keep the proximity between inlet and outlet ozone concentrations, which makes the reaction cell a differential reactor.<sup>27</sup> The inside diameter of the ring was 4.6 cm. Prior to each experiment, the Teflon film was cleaned by the same fragrance-free detergent and deionized water and then exposed to the high-concentration ozone in the FLEC until the outlet ozone level was steady.

### Experimental apparatus

A stainless steel test cell known as FLEC (CHEMATEC, Roskilde, Denmark)<sup>28,29</sup> was used to measure the heterogeneous reactions between clothing and ozone. The air velocity in the FLEC is relatively steady because of its cone-shaped inner upper surface of the instrument.<sup>28</sup> Under normal test conditions, the air flow in FLEC is laminar, and the air flow rates are also controllable.<sup>28,29</sup> For these reasons, FLECs are widely used in testing surface emissions.<sup>17,28</sup> In this study, we use FLEC to study the heterogeneous surface-ozone reactions.

The experimental system, as shown in Figure 1, consists of an ozone generator, an air pump, a mass flow controller, an FLEC and an ozone monitor. Ozone was generated by the Ozone Calibration Source (Model 306, 2B Technology, Boulder, USA), which can generate a specified concentration of ozone between 0 and 2000 ppbv. The ozone concentration was monitored with a Photometric Ozone Analyzer (Model 205, 2B Technology, Boulder, USA), which has a precision of 1.0 ppbv. The mass flow controller (serial #: 70030, Alicat Scientific, Tucson, USA) was used to control the air flow rate and was calibrated using a flow



**Figure 1.** Schematic of experimental apparatus for kinetic constants determination of ozone-initiated reaction with clothing. FLEC: field and laboratory emission cell.

meter (Defender 520, BIOS, Butler, USA). The temperature and relative humidity at the outlet of the FLEC were measured by a temperature and humidity transmitter (JWSL-4, Kunlunhaian, Beijing, China). In order to reduce the background particle concentrations, 5–6 micron pore size Teflon Particle Filters were installed before the inlets to the air pump and ozone generator.

### Test procedures

The interior surface of the FLEC was cleaned with sodium hydroxide solution and deionized water before use. During the initial 10 min, the supply air with a certain concentration of ozone flowed through the bypass channel. The inlet ozone concentration was measured continuously at sampling point A (as shown in Figure 1). After the initial 10 min, the air flow was switched to the FLEC, and the outlet ozone concentration was measured at sampling point B for 60 more min, at which point the experiment was considered to be complete. Ozone concentration, air flow velocity and soiling time of vest are considered as important factors that could influence ozone-cotton vest reactions. During each experiment, only one factor was varied while keeping other factors constant in order to determine the major factor. The flow rate varied within the range between 0.12 m<sup>3</sup>/h and 0.23 m<sup>3</sup>/h, which is equivalent to an air velocity of 0.07 m/s to 0.14 m/s across the cross-section inside FLEC based on the Zhang and Niu's study.<sup>30</sup> The ozone concentration passing through the inlet of FLEC was controlled to give 0 ppbv to 170 ppbv inside the FLEC. The soiling hours of vests were 0 to 36 h. Fifty-three sets of experiments were conducted as shown in Table 1.

### Determination of deposition velocity and reaction kinetic constants

The kinetic mechanism of the ozone-clothing reactions in the FLEC can be schematically summarized in Figure 2(b), which describes the mass balance of a finite element in the cross-section of the FLEC. The deposition of ozone on the FLEC's interior surfaces is negligible as supported by the result presented in section 'Results'. The heterogeneous reaction is assumed to be of first order with respect to the gas-phase concentration of ozone. Besides, the reaction is considered to have reached steady state if it rapidly reaches equilibrium and remains stable for an extended period. Under these circumstances, the mass conservation equation in the finite element of the FLEC, and the boundary condition on the clothing surface can be described by equations (1) and (2) as follows

$$GdC_b - 2\pi rkC_s dr = 0 \quad (1)$$

$$kC_s = h_m(C_b - C_s) \quad (2)$$

where  $G$  is the flow rate of the inlet air, m<sup>3</sup>/s;  $C_b$  is the ozone concentration of the main stream, ppbv;  $C_s$  is the ozone concentration near the clothing surface, ppbv;  $r$  is the local radius of the FLEC, m;  $k$  is the reaction rate constant of the reaction surface (a parameter to evaluate the reaction rate of the surface reaction), m/s;  $h_m$  is the convective mass transfer coefficient at the FLEC surface, m/s.

Combining equations (1) and (2) yields equation (3)

$$GdC_b - 2\pi r \frac{k \cdot h_m}{k + h_m} C_b dr = 0 \quad (3)$$

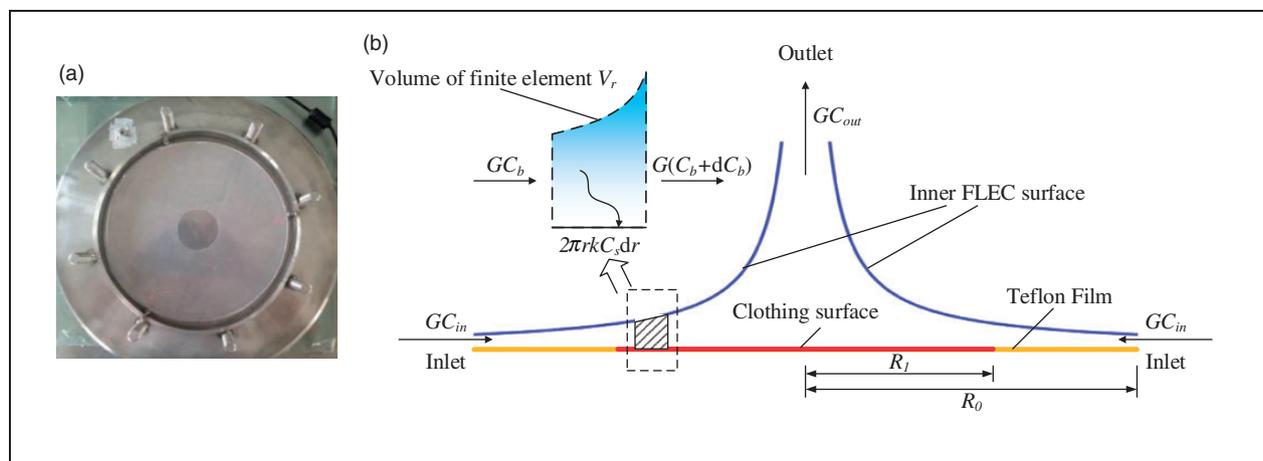
**Table 1.** Details of the experimental conditions and key results from the study of deposition velocity for ozone reactions with human clothing.

No.	Ozone concentration (ppbv)	Temperature (°C)	Relative humidity (%)	Hours the vest was worn (h)	Air flow velocity (m/s)	Deposition velocity (cm/s)
1	21	23.2	51.1	6	0.12	1.00
2	47	23.1	51.4	6	0.12	0.54
3	69	22.9	52.0	6	0.12	0.72
4	106	23.1	51.8	6	0.12	0.92
5	131	26.2	45.0	6	0.12	0.71
6	160	27.4	42.7	6	0.12	0.86
7	15	24.5	69.4	12	0.10	0.72
8	40	24.7	69.5	12	0.10	0.65
9	70	24.8	69.7	12	0.10	0.68
10	103	24.9	64.7	12	0.10	0.66
11	127	25.1	68.3	12	0.10	0.60
12	163	22.6	32.9	12	0.10	0.87
13	159	21.3	34.1	12	0.11	0.87
14	17	25.0	36.5	12	0.12	1.11
15	45	25.6	36.8	12	0.12	1.12
16	72	27.6	40.9	12	0.12	0.92
17	100	24.2	69.3	12	0.12	0.73
18	132	24.3	69.4	12	0.12	0.70
19	162	24.4	69.8	12	0.12	0.70
20	102	22.9	33.4	12	0.12	0.95
21	135	23.4	35.0	12	0.12	0.93
22	161	21.8	33.1	12	0.12	0.84
23	163	21.3	30.7	12	0.12	1.04
24	165	24.6	34.9	12	0.12	0.92
25	164	24.2	31.3	24	0.10	0.56
26	17	24.2	32.1	24	0.12	0.94
27	38	24.1	32.5	24	0.12	0.73
28	70	24.2	32.7	24	0.12	0.76
29	100	24.3	31.9	24	0.12	0.75
30	132	24.6	31.9	24	0.12	0.70
31	168	21.8	31.5	24	0.12	0.69
32	159	–	–	36	0.07	0.86
33	157	–	–	36	0.09	1.00
34	129	–	–	36	0.11	0.68
35	156	–	–	36	0.11	0.75
36	47	–	–	36	0.13	0.84
37	70	–	–	36	0.13	0.65
38	94	–	–	36	0.13	0.70
39	127	–	–	36	0.13	0.56
40	129	–	–	36	0.13	0.67
41	159	–	–	36	0.13	0.88
42	18	28.7	28.2	Laundered	0.12	0.52
43	37	28.5	28.4	Laundered	0.12	0.62
44	69	27.6	33.1	Laundered	0.12	0.60

(continued)

Table 1. Continued

No.	Ozone concentration (ppbv)	Temperature (°C)	Relative humidity (%)	Hours the vest was worn (h)	Air flow velocity (m/s)	Deposition velocity (cm/s)
45	99	27.3	30.7	Laundered	0.12	0.47
46	129	26.4	31.4	Laundered	0.12	0.44
47	159	21.6	35.0	Laundered	0.12	0.38
48	42	29.8	26.6	Teflon film	0.12	0.023
49	106	28.6	25.4	Teflon film	0.12	0.020
50	163	31.1	25.1	Teflon film	0.12	0.014
51	160	–	–	Teflon film	0.13	0.019
52	157	–	–	KI-coated	0.10	1.08
53	164	–	–	KI-coated	0.12	1.26



**Figure 2.** Kinetic mechanism of the ozone-clothing reactions in the FLEC: (a) Teflon film ring and fixing apparatus of the experiment; (b) finite element of ozone-clothing reaction in the cross-section of FLEC. FLEC: field and laboratory emission cell.

The deposition velocity,  $v_d$  for the reaction, has been extensively used to examine the ozone removal; as is defined by equation (4)<sup>31</sup>

$$\frac{1}{v_d} = \frac{1}{k} + \frac{1}{h_m} = \frac{4}{\gamma\langle v \rangle} + \frac{1}{h_m} \quad (4)$$

where  $\gamma$  is the ozone reaction probability<sup>31</sup>;  $\langle v \rangle$  is the Boltzmann velocity,<sup>31</sup> which has a value of  $3.6 \times 10^4 \text{ cm s}^{-1}$  for ozone at 293 K. The reaction rate constant,  $k$ , is equal to  $\gamma\langle v \rangle/4$ .

For each experiment, the deposition velocity was assumed to be a constant at the reaction surface for a differential reactor,<sup>27</sup> as shown in Figure 2(b). Thus, the deposition velocity would be approximately constant in every place on the clothing surface and Teflon film, respectively.

The solution of  $v_d$  can be calculated by equations (3) and (4)

$$v_d = \frac{G}{\pi r_1^2} \ln\left(\frac{C_{in}}{C_{out}}\right) - \frac{r_0^2 - r_1^2}{r_1^2} v_{d\_teflon} \quad (5)$$

where  $r_0$  is the radius of the test area of the FLEC, m;  $r_1$  is the radius of the reaction area of the test specimen (the inner radius of the ring-shaped Teflon film), m;  $C_{in}$  is the ozone concentration at the FLEC inlet, ppbv;  $C_{out}$  is the ozone concentration at the FLEC outlet, ppbv;  $v_{d\_teflon}$  is the deposition velocity of Teflon film surface, m/s.

The convective mass transfer coefficient,  $h_m$ , was obtained by conducting the same experiment using a vest sample that was coated with potassium iodide (KI), as this would be a perfect sink for ozone.<sup>32</sup>

The KI-coated vest sample was prepared by dipping the fabric into a KI solution and then allowing the fabric to dry in an oven set at 60°C. The reaction rate constant,  $k$ , was assumed to be infinite at the KI-coated vest surface. That is, the deposition velocity,  $v_d$ , in equation (4) would represent  $h_m$  for the experiment. Test specimens coated with KI were achieved by using the dip-coating method. Each specimen (radius = 10 cm) was positioned in a glass dish. Pure water of 50 mL and KI of 16 mg were well mixed and added into the dish. The dish was placed into an oven at a temperature of 60°C until the pure water was completely evaporated. Given  $v_d$  and  $h_m$ , the reaction rate constant for ozone on the vest can be calculated using equation (4).

## Results and discussion

### Deposition velocity

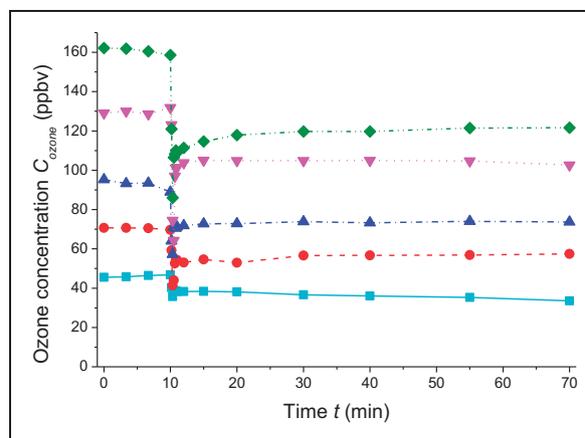
This section discusses the results of ozone deposition velocity of ozone-initiated reactions with a cotton vest and analyses the influence of different factors on the deposition velocity. Table 1 shows the detailed results for each experiment.

### Deposition velocity measurement for FLEC background

The background consumption sites of ozone consist of the FLEC's interior surfaces and the Teflon film covering. Background tests were conducted by placing the FLEC on an aluminium plate with/without the Teflon film covering. The ozone level at the outlet of the FLEC was approximately equal to that at the FLEC inlet when the Teflon film was not used. Hence, the FLEC, including the aluminium plate, has negligible influence on the deposition velocity measurement. The ozone deposition velocity on the Teflon film,  $v_{d\_teflon}$ , was measured by the same method mentioned above, but without the test specimen below the Teflon film. The results showed that the Teflon film removes about 5% of the ozone when the inlet ozone concentrations were within the range of 42 to 163 ppbv. The detailed results are shown in Table 1 (case 48–51). The average deposition velocity on Teflon film was 0.019 cm/s.

### Effect of ozone concentration on deposition velocity

The effect of inlet ozone concentration on the time-concentration profiles in the outlet air is shown in Figure 3. Other conditions are similar in all five cases (case 36, 37, 38, 40, 41 in Table 1). The discontinuity at  $t = 10$  min in Figure 3 was caused by switching the sampling location from inlet air to outlet air. The temporal



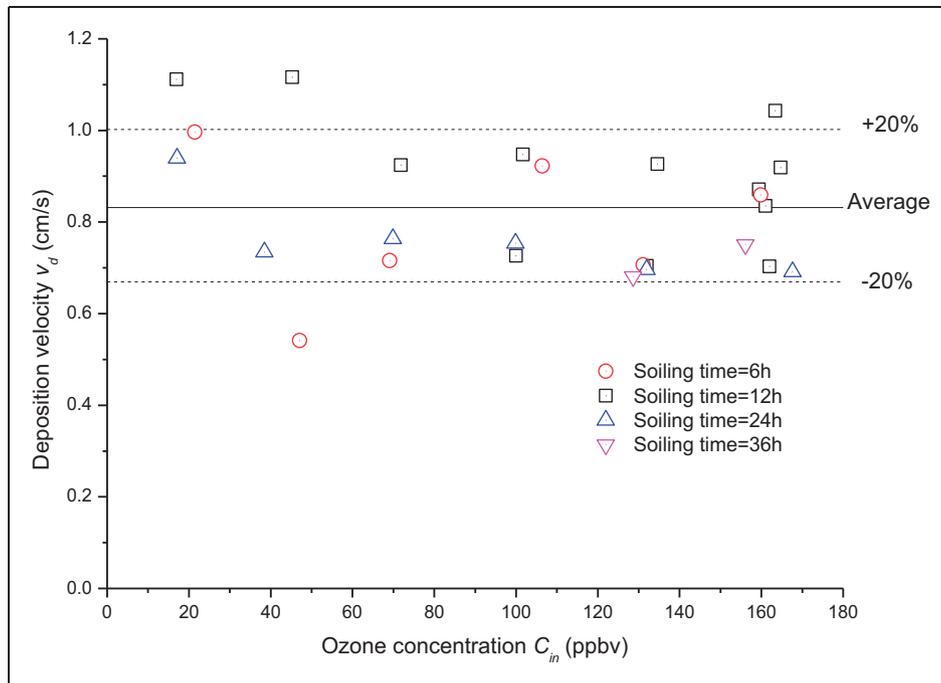
**Figure 3.** Temporal variations of ozone concentration at sampling point A (0–10 min) and B (after 10 min) for the ozone reaction with the soiled test specimen at different inlet ozone concentrations.

variations in the ozone concentrations followed a similar trend. Ozone removal was fast initially and then declined to a moderate rate in the end. The reactions reached a steady state quickly (<5 min), and the reaction process remained steady for a long time (>1 h). This result has provided a validation of the rationality of the steady state hypothesis made in equation (1).

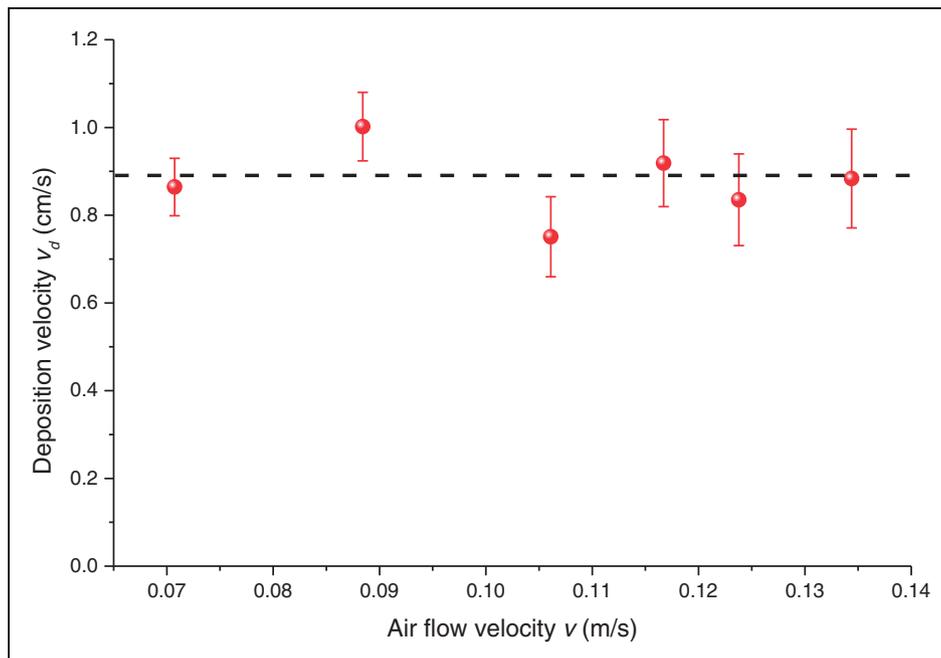
Figure 4 illustrates the deposition velocity for different ozone concentrations. The air flow velocities of all cases shown in Figure 4 are approximately the same and in the range of 0.11–0.12 m/s. Other parameters are also similar in all cases. Statistical analysis using t-distribution hypothesis testing shows that deposition velocities for different experiments were not significantly different at the 95% confidence level. Deposition velocities at low ozone concentrations were relatively higher than the rest. A probable reason could be due to the low precision of the ozone monitor in the low concentration range. The stability of the deposition velocity at different ozone concentrations proves that the ozone reaction with surfaces that have large quantities of reactant species would generally follow the first-order mechanism,<sup>24,33</sup> which is the prerequisite for equations (1) and (2).

### Effect of air flow velocity on deposition velocity

Figure 5 illustrates the deposition velocities at different air flow velocities. Other conditions were similar in all six cases (cases 22, 24, 32, 33, 35, 41 in Table 1). The air flow velocities tested covered a wide range, from 0.07 to 0.14 m/s). In order to characterize the effect of air flow velocity accurately and lower the experimental uncertainties, the ozone concentrations in all six cases were



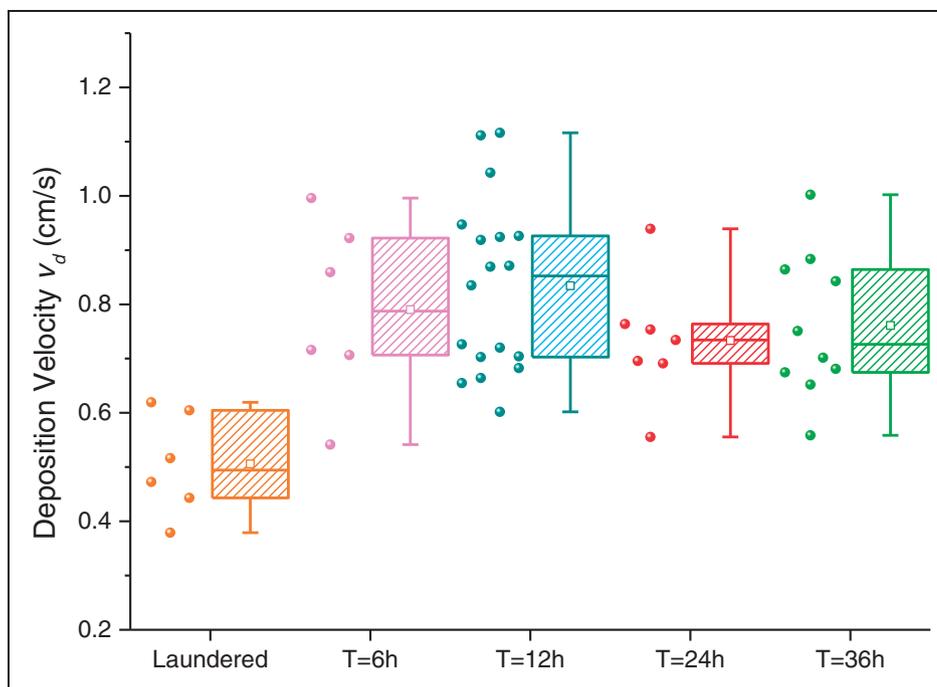
**Figure 4.** Effect of ozone concentration on deposition velocity onto soiled test specimen.



**Figure 5.** Effect of air flow velocity on deposition velocity of ozone-initiated reactions with the soiled test specimen.

set at a high level (160 ppbv). The results showed that deposition velocities varied only slightly with different air flow velocities. This result is somewhat different from previous studies,<sup>20,21</sup> which showed that a significant change in the air change rate could contribute to a

change in deposition velocity. However, none of these experiments measured the surface air flow velocity of ozone-clothing reactions. The insignificant difference in deposition velocity observed in the present study was probably due to the large mass transfer coefficients,



**Figure 6.** Effect of clothing-wearing time on deposition velocity of ozone-initiated reactions with the soiled specimen. (The bottom and top of the box are the first and third quartiles, the band inside the box is the median, white pot inside the box is the average, and the ends of the whiskers represent the minimum and maximum of all of data.)

which was about 42 m/h (1.17 cm/s) when the surface flow velocities were in the range of 0.07 to 0.14 m/s. Our value is in agreement with the upper bold line in Figure 4 of Pandrangi and Morrison's paper.<sup>20</sup>

### Effect of surface condition on deposition velocity

Figure 6 shows the deposition velocities for different soiling times based on all experimental results in this study. The results show that the laundered and soiled test specimens differed significantly. The average deposition velocities for 6-, 12-, 24- and 36-h soiling were 0.79, 0.83, 0.73 and 0.76 cm/s, respectively. No significant difference was observed with the soiling times. This indicated that when, soiling time was over 6 h, it had little effect on deposition velocities. We thus speculate that the concentration of skin oils on the surface of the vest would remain roughly constant after 6 h. On the other hand, whether or not the vest had been soiled did have an effect. The mechanism of the soiling process was not examined in this study.

### Convective mass transfer coefficient and reaction rate constant

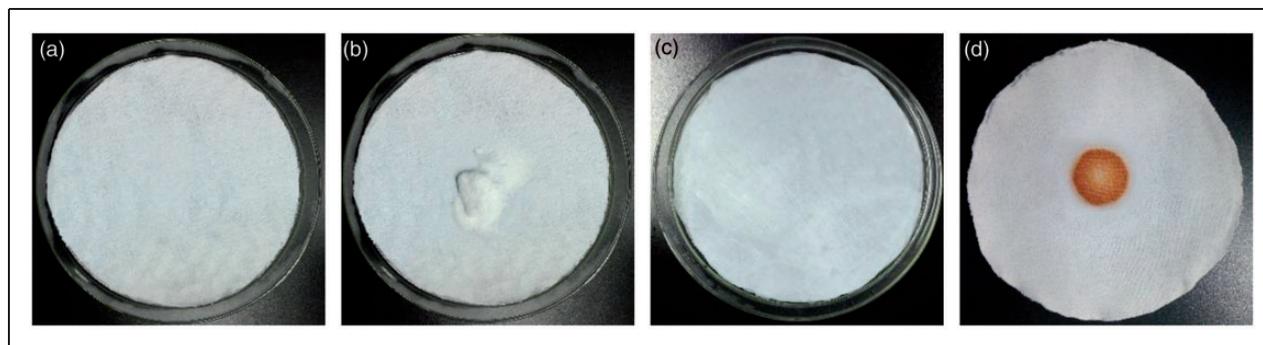
Figure 7(a) to (c) illustrates the procedures of the dip-coating method, and Figure 7(d) shows the KI-coated

specimen after the experiment. The spot area in the middle of the specimen is covered by the product of the ozone-KI reaction. This experiment was conducted under different ozone concentrations, air velocities and soiled hours, and the results showed no significant difference in all cases. Figure 8 compares the average deposition velocities for the laundered, soiled and KI-coated specimens. The deposition velocity of KI-coated specimen is the same as the convective mass transfer coefficient, since the reaction rate constant of KI-ozone reaction is infinite. Hence, the deposition velocity of the KI-coated specimen ( $1.17 \pm 0.10$  cm/s) was higher than for the soiled specimen ( $0.79 \pm 0.17$  cm/s) under the same conditions.

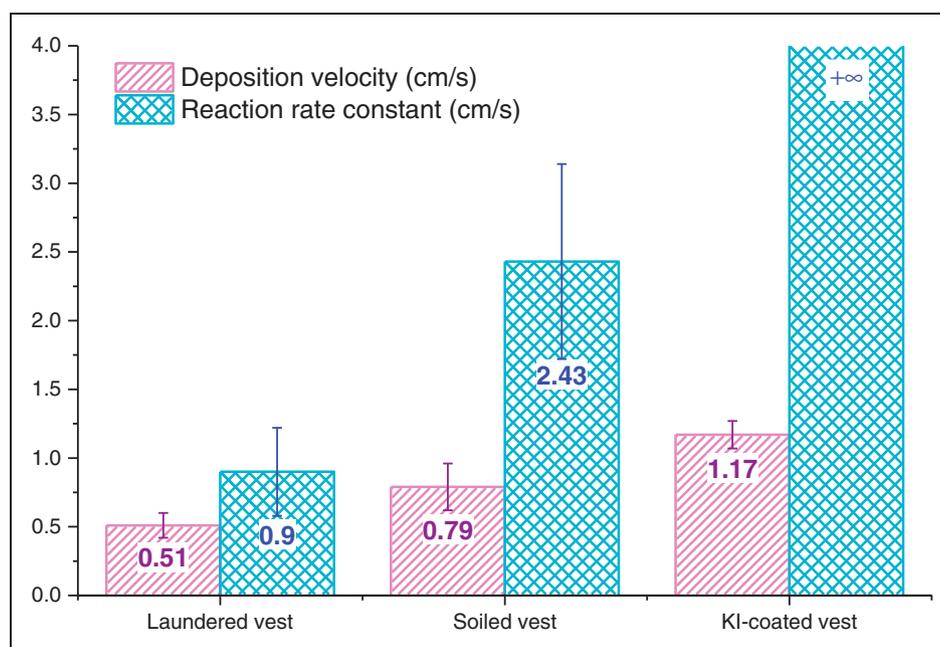
Given the values of the deposition velocity and mass transfer coefficient, the reaction rate constant can be calculated using equation (4). The reaction rate constants of laundered and soiled cotton specimens are  $0.90 \pm 0.32$  and  $2.43 \pm 0.71$  cm/s, respectively.

### Comparisons of kinetic constants with other studies

Zhang and Niu<sup>30</sup> examined the convective mass transfer coefficient of an FLEC using both numerical modelling and experimentation. However, their experiment only determined the mass transfer coefficient with a water surface, and their result (0.27 cm/s) was much



**Figure 7.** Illustrations of KI-coated test specimen experiment: (a) laundered cotton specimen; (b) laundered cotton specimen with solid KI; (c) cotton specimen immersed in KI solutions; (d) KI-coated specimen after ozone experiment.



**Figure 8.** Ozone deposition velocity and reaction rate constant for laundered specimen, soiled specimen and KI-coated specimen.

lower than the value we obtained through KI-coating tests (1.17 cm/s). This difference could be attributed to the different conditions of the surfaces in these two experiments. The cotton vest surface has a much higher roughness compared to a smooth water surface. Therefore, Zhang and Niu's result may not be suitable to ordinary indoor surfaces.

The deposition velocities for soiled cotton clothing measured in this experiment, including both soiled and unsoiled vests, are higher than those reported in other studies (as shown in Table 2). Previous investigations on ozone deposition velocities were based on tests conducted under real environmental conditions. Either chamber tests or simulated room tests

measure the deposition velocity of the entire vest, a lump of various surfaces. The deposition velocities measured by these methods are the average deposition velocity on clothing or human surfaces, where surface air flow velocities are not measured or controlled. Thus, the average deposition velocity measured by previous studies (Table 2) cannot be extended into other cases. Some human surfaces have a lower velocity, including the horizontal surface of a thigh when a person is seated. As a result, the deposition velocities measured in other studies are probably controlled by external convective mass transfer, which reduces the deposition velocity according to equation (4).

**Table 2.** Comparison of ozone deposition velocity on cotton clothing determined by different studies.

Items	This study	Coleman et al. <sup>26</sup>	Rai et al. <sup>21</sup>	Tamas et al. <sup>24</sup>	
Reaction condition	FLEC (35 mL)	Chamber (10.5 L)	Chamber (5.2 m <sup>3</sup> )	Chamber (31 m <sup>3</sup> )	
Deposition velocity to background (cm/s)	0.019	–	–	–	–
Deposition velocity on laundered clothing (cm/s)	0.51	0.30	0.13	–	–
Deposition velocity on soiled clothing (cm/s)	0.79	0.41	0.23	0.27	0.19
Deposition velocity difference <sup>a</sup> (cm/s)	0.28	0.11	0.10	–	–
Deposition velocity, percent changes <sup>b</sup>	35.4%	26.8%	43.5%	–	–
Deposition velocity on KI-coated clothing (cm/s)	1.17	0.61	–	–	–
Air flow velocity (m/s)	0.07–0.14	–	–	–	–
Air change rate (h <sup>-1</sup> )	3400–6500	23	0.5	3(20) <sup>c</sup>	6.5(16.7) <sup>c</sup>

<sup>a</sup>Deposition velocity difference means the difference in deposition velocities on laundered and soiled clothing.

<sup>b</sup>Deposition velocity percent changes means the percentage of deposition velocity difference divided by the deposition velocity on the soiled clothing.

<sup>c</sup>The number in parenthesis means the recirculation rate.

The roughness of clothing surface has a strong effect on the convective mass transfer coefficient and the deposition velocity of ozone-clothing reaction. The results obtained in our investigation can be used to simulate the ozone reaction around the breathing zone, since the reaction conditions, such as air flow velocity, can be described in detail under these circumstances.

## Conclusions

An experimental method using FLEC to examine the kinetics parameters of ozone-initiated reactions with clothing was developed by this study. The experimentally determined deposition velocity and reaction rate constant of ozone-initiated reactions with soiled cotton vest are, on average,  $0.79 \pm 0.17$  and  $2.43 \pm 0.71$  cm/s, respectively. This method shortens the experimental duration of ozone-clothing experiments. The deposition velocity and reaction rate constant were unaffected by indoor environmental conditions (air flow velocity and ozone concentration) and soiling time of clothing (>6 h). However, whether or not the clothing had been worn (i.e. soiled versus unsoiled clothing) is an important factor that can affect the deposition velocity. Overall, the ozone deposition velocities of ozone-soiled cotton clothing reactions are approximately constant under normal indoor conditions.

## Authors' contribution

All authors contributed equally in the preparation of this manuscript.

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## Declaration of conflicting interests

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