Original Paper

Special articles: JCREN II

特集: JCREN II

Dependence of Oxygen Concentration and Temperature on the Growth Rate Distribution of SiO₂ Solid Film by Chemical Vapor Deposition in the Hexamethyldisiloxane-oxygen System

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(Received February 8, 2021)

In this paper, the growth rate distribution of SiO₂ solid film by chemical vapor deposition (CVD) under a reduced pressure of 25,000 Pa has been investigated experimentally and numerically. The activation energy of the apparent surface reaction taking no particle formation into consideration was 335 kJ/mol. For all experimental conditions, the experimental results for the growth rate of CVD could be reproduced by the calculation ones before the maximum growth rate when mass transfer could be controlled by the apparent surface reaction. On the other hand, the calculation results for the growth rate of CVD disagreed to some extent with the experimental results after the maximum growth rate when mass transfer could be controlled by diffusion. By the observation of SEM images, the mass transfer in this CVD could include not only surface reaction but also particle formation. It was also suggested that the diffusion coefficient could become the apparent diffusion coefficient with the effect of particle formation. In future work, according to the estimation of the particle formation rate by using a membrane filter, the growth rate distribution could be reproduced by numerical calculation with not only surface reaction but also particle formation.

本論文では、25,000 Pa という減圧条件において化学気相蒸着法 (CVD) を用い、SiO₂ 固体膜の成長速度分布を実験的および数値的に調査を行った。粒子生成を考慮しない場合の見かけの表面反応における活性化エネルギーは 335 kJ/mol であった。また、物質移動が見かけの表面反応律速と想定される、最大成長速度よりも上流側では、全ての実験条件において、数値解析により CVD による成長速度の実験結果を再現することができた。一方で、物質移動が拡散律速と想定される、最大成膜速度以降の領域では、数値解析結果により CVD による成長速度の実験結果を再現することができない部分があった。SEM 観察による画像からは、本論文の CVD における物質移動には表面反応だけでなく粒子生成も含まれる可能性が考えられた。また、粒子生成の影響から、拡散係数が見かけの係数となる可能性があることも示唆された。今後、メンブレンフィルターを用いた粒子生成速度を推定し、さらに表面反応だけでなく粒子生成を考慮した数値計算を行い、成長速度分布を再現できるモデル化が可能となると考えられる。

Key Words

Reduced-pressure CVD, Apparent surface reaction, CFD, SiO₂ particulate film

1. Introduction

The thermal CVD (chemical vapor deposition) method creates a thin film on a heated substrate during chemical reactions from vapor raw material and has been widely used due to its many advantages¹⁾. In order to use thermal CVD for many applications, it is necessary to investigate not only heat transfer with fluid flow but also mass transfer with kinetics of chemical reactions and diffusion coefficient^{2)~6)}.

There have been two methods of measuring the growth rate on a substrate by thermal CVD²⁾⁷⁾. The first method is to measure the mass difference of the substrate in the CVD reactor before and after experiments²⁾. The second method is to measure the film thickness on the substrate by using SEM (scanning electron microscope) images⁷⁾.

In our previous report⁸⁾, the growth rate distribution of deposited SiO₂ in the HMDSO (hexamethyldisiloxane, O[Si(CH₃)₃]₂-O₂ (oxygen) system along the flow axis was measured by the mass difference of the substrates under a pressure of 50,000 Pa. The growth rate had a maximum

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value and then decreased drastically with the distance from the inlet. The calculation results of growth rate distribution with CFD (computer fluid dynamics) did not agree with the experimental results because particle formation could not be ignored in the CVD process under a pressure of 50,000 Pa. Thin film formation of SiC (silicon carbide) by thermal CVD in the SiH_4 (mono-silane)– C_6H_6 (benzene) system was reported by Oyamada *et al.*⁹⁾ They suggested that the lower the total pressure in the reactor was, the lower the particle formation was⁹⁾.

Therefore, in order to suppress particle formation during SiO_2 CVD in our experimental apparatus⁸⁾, it is necessary to reduce the pressure to less than 50,000 Pa.

In this study, the growth rate distribution of SiO_2 solid film by thermal CVD in the HMDSO– O_2 system under a reduced pressure of 25,000 Pa has been investigated experimentally and numerically. Furthermore, SEM observation of the deposited material on the substrate was also conducted to investigate the surface configuration of the deposited material.

2. Experimental

Fig. 1 shows that the experimental equipment consists of mass flow controllers of nitrogen (N_2) gas and O_2 , a reactor, and an aspirator to reduce the reaction pressure. In this study, the path and tank were changed to stainless steel to the extent possible to keep the reduced pressure. In addition, a needle valve for pressure adjustment

was installed at the outlet of the reactor. HMDSO in a stainless-steel tank was used as the raw material. The temperature of the liquid HMDSO in the tank was kept at 283 K by a thermostatic chamber (EYELA, UNI COOL BATH NCB - 120). A quartz tube (outer diameter: 13 mm, inner diameter: 10 mm, length: 1000 mm) was used as the reactor, which was heated by an electric furnace (Chugai and Plox Co., Ltd., R32/250/12-P320). In order to evaluate the growth rate of silicon dioxide (SiO_2), 36 short quartz tubes (outer diameter: 9 mm, inner diameter: 7 mm, length: 5 to 20 mm) as the substrate were installed in the heated section (length: 400 mm) in the reactor. Before the experiments, the mass of the short quartz tubes was measured. While N_2 gas was fed into the reactor, the temperature at the outer wall of the reactor was raised to the desirable setting temperature on the outer wall of the tubular reactor T_s which was regulated by the thermostat of the electric furnace. When the wall temperature approached T_s , the desired mole fraction of HMDSO vapor was supplied to the reactor from the tank by bubbling with another N_2 gas. At the same time, the desired mole fraction of O_2 was also supplied. The mass flow rate of the HMDSO vapor was calibrated beforehand by the bubbling gas flow rate of N_2 and temperature of the liquid material in the tank. Then, the chemical reaction started as the following Eq. (1).

The vapor of HMDSO was collected by a cold trap in the liquid N_2 and measured just before the CVD

Fig. 1 Experimental equipment for SiO_2 film coating by thermal chemical vapor deposition

experiment. The total gas flow rate and total pressure were 300 SCCM (standard cubic centimeter per minute) and 25,000 Pa, respectively. The T_s was changed from 1273 K to 1473 K. The mole fraction of O_2 was also changed from 0.089 to 0.285. The mole fraction of HMDSO was about 0.0156. The reaction was performed in 100 minutes. After the experiment, the vapor of HMDSO remaining in the reactor was flushed by N_2 gas for 60 minutes. Table 1 shows the experimental conditions.

After the experiments, the growth rate of deposited SiO_2 on the short quartz tube was calculated by the following Eq. (2).

$$G_{SiO_2,i} = \frac{m_i - m_{0,i}}{S_i \Delta t} \quad (2)$$

Here, $G_{SiO_2,i}$, m_i , $m_{0,i}$, S_i , and Δt show the growth rate of deposited SiO_2 of the i -th quartz tube [$kg/m^2/s$], mass of the i -th quartz tube after the experiments [kg], mass of the i -th quartz tube before the experiments [kg], inner surface area of the i -th quartz tube [m^2], and reaction time ($= 6000$ s), respectively.

The total mass of deposited SiO_2 was calculated by the following Eq. (3).

$$\Delta M = \sum_{i=1}^{36} (m_i - m_{0,i}) \quad (3)$$

The surface configuration of deposited SiO_2 on the short quartz tube at the maximum growth rate was

Table 1 Experimental conditions

	Initial O_2 mole fraction, x_{O_2}	Setting temperature on the outer wall of the tubular reactor, T_s [K]
(i)	0.089	1273
(ii)	0.165	1273
(iii)	0.285	1273
(iv)	0.285	1323
(v)	0.285	1373
(vi)	0.285	1423
(vii)	0.285	1473

observed by SEM (scanning electron microscope).

3. Numerical Simulation

Two-dimensional numerical simulation in the horizontal reactor in the $O[Si(CH_3)_3]_2-O_2-N_2$ system was conducted. The governing equations, calculation domain, and boundary conditions for numerical simulation were reported in our previous report⁸⁾. The governing equations and the boundary conditions were discretized by the finite volume method and solved by the THOMAS method. The velocity and pressure profiles were solved by the SIMPLE algorithm. From our previous report⁸⁾, $(M_r, M_z) = (100, 12000)$ was adopted as the grid sensitivity of the growth rate distribution along the flow axis.

4. Results and Discussion

4.1 Growth rate distribution of the SiO_2 film

Fig. 2 shows both the semi-log plot of the growth rate distribution of the SiO_2 film and normal plot of temperature distribution along the flow axis. In Fig. 2 (a), in which the initial O_2 mole fraction was changed under the condition of $T_s = 1273$ K, film formation started at the point of about $z = 0.08$ m under any initial O_2 mole fraction condition. The growth rate and the temperature also increased with the position at $0.08 \text{ m} < z < 0.11 \text{ m}$. In the section after $z = 0.12$ m, the growth rate decreased exponentially with the distance from the heater inlet. The tendency of the growth rate distribution after $z = 0.12$ m was almost the same even if the O_2 concentration was changed. We can see that the maximum growth for $x_{O_2,init} = 0.089$ was lower than that for $x_{O_2,init} = 0.165$ and 0.285 .

Mass transfer in CVD has been reported to consist of three rate-limiting processes³⁾: (i) diffusion of raw material, (ii) gas phase reaction, and (iii) surface reaction. In this study, the gas phase reaction is assumed to be the fastest

Fig. 2 Growth rate and wall temperature distributions along the flow axis of the horizontal tube reactor. (a) Dependence of O_2 molar fraction, (b) Dependence of temperature

of these three processes, and mass transfer is considered to be composed of (i) diffusion of raw material and (iii) surface reaction. As shown in Fig. 2 (a), at first, as the growth rate increased with temperature, the mass transfer could be controlled by surface reaction. Here, surface reaction refers to the reaction in which the precursor of the deposited material is converted to a solid film on the substrate. On the other hand, in the region after the maximum growth rate, mass transfer could be controlled by diffusion of the precursor^{3) 6)}. For this region, the gradient of the growth rate to the distance from the heater inlet on the semi-log plot was utilized to estimate the diffusion coefficient. Here, the temperature of the substrate along the distance from the heater inlet was almost constant.

In Fig. 2 (b), the position of the maximum growth rate moved to the upstream side with increase in T_s because the surface reaction could be promoted. In the diffusion-controlled region, the growth rate decreased exponentially along the distance from the heater inlet at $T_s \leq 1373$ K. However, the growth rate decreased with large variation along the distance from the heater inlet at $T_s \geq 1423$ K and $z > 0.15$ m.

Table 2 shows the total mass of deposited SiO_2 on the substrates. From this table, the result is extremely

Table 2 Dependence of total mass of deposited SiO_2 on the substrates in the experimental conditions

Experimental condition	Total mass of deposited SiO_2 , ΔM [kg]
(i)	0.00019
(ii)	0.00027
(iii)	0.00026
(iv)	0.00038
(v)	0.00037
(vi)	0.00027
(vii)	0.00025

small when $x_{\text{O}_2, \text{init}} = 0.089$. Fig. 3 shows photographs of the formed film immediately at the maximum growth rate for several conditions as listed in Table 1. In Fig. 3 i), ii), and iii), the thin brownish film changed to translucent white as the initial O_2 mole fraction increased. From the results of Table 2 and Fig. 3, it was suggested that the more the initial O_2 mole fraction could cause not only the more the total mass of deposited SiO_2 but also the change in the type of film. As the colors of the substrate were almost translucent at $x_{\text{O}_2, \text{init}} = 0.285$, we assumed that a single crystal of SiO_2 could be formed. In Fig. 3 iii), iv), v), vi), and (vii), when the T_s increased, the color of the film changed from transparent white to transparent brown and then to fully transparent at $T_s \leq 1373$ K. However, the color of the film changed again to transparent white at $T_s \geq 1423$ K.

This indicates that the difference in the type of film formed by changing the T_s may be the cause of the above-mentioned tendency in the diffusion-controlled region.

4.2 Surface reaction rate constant

The growth rate distribution in the region of the surface reaction rate controlled was applied to the differential reactor model reported by Hatori *et al.*⁶⁾ and Kurihara *et al.*⁸⁾ From the mass balance equation using this model, the mass flow rate of each component (HMDSO , N_2 , O_2 , CO_2 and H_2O) at each quartz short tube was calculated. Next, from the value of the mass flow rate, the mole fraction of HMDSO at each quartz short tube was calculated. The procedure was the same as that in our previous reports^{6) 8)}. Note that the chemical reaction during SiO_2 film coating was assumed to be the first-order chemical reaction of HMDSO and O_2 in this study. Then, growth rate N_{SiO_2} [mol/m²/s] was expressed as follows:

Fig. 3 Photographs of the formed thin film on the substrate under several conditions as listed in Table 1

Fig. 4 Arrhenius plot of the surface reaction rate constant

$$N_{\text{SiO}_2} = \frac{G_{\text{SiO}_2}|_{i+\frac{1}{2}}}{M_{\text{SiO}_2}} = k_s|_{i+\frac{1}{2}} C_{\text{HMDSO}}|_{i+\frac{1}{2}} C_{\text{O}_2}|_{i+\frac{1}{2}} \\ = k_s|_{i+\frac{1}{2}} \frac{C_{\text{HMDSO}}|_i + C_{\text{HMDSO}}|_{i+1}}{2} \frac{C_{\text{O}_2}|_i + C_{\text{O}_2}|_{i+1}}{2} \quad (4)$$

Here, C_{HMDSO} [mol/m³] and C_{O_2} [mol/m³] show the molar concentrations of HMDSO and O₂, respectively.

Therefore, the surface reaction rate constant k_s [m/s] could be given by

$$k_s|_{i+\frac{1}{2}} = \frac{N_{\text{SiO}_2}|_{i+\frac{1}{2}}}{M_{\text{SiO}_2} C_{\text{HMDSO}}|_{i+\frac{1}{2}} C_{\text{O}_2}|_{i+\frac{1}{2}}} \quad (5)$$

Fig. 4 shows an Arrhenius plot of the surface reaction rate constant. The surface reaction rate constant could be represented by a single correlation line with a correlation coefficient of 0.62 regardless of the initial O₂ mole fraction. The surface reaction rate constant shown in Eq. (6) was obtained.

$$k_s = 8.5 \times 10^{12} \exp\left(-\frac{335000}{R_0 T_{\text{IW}}}\right) \quad (6)$$

Here, T_{IW} [K] is the wall surface temperature. The activation energy value of the surface reaction rate constant ΔE was 335 kJ/mol.

Even if the T_s was higher than 1373 K, the effective wall temperature range for the surface reaction rate constant was at 1139 K < T_{IW} < 1219 K. Therefore, we used all experimental conditions for the Arrhenius plots of the surface reaction rate constant.

4.3 Diffusion coefficient

Diffusion coefficient D [m²/s] in CVD was reported by Akiyama *et al.*³⁾ and given by

$$D = -\frac{d(\ln G_{\text{SiO}_2})}{dz} r^2 u \frac{1}{Sh} \quad (7)$$

Here, $d(\ln G_{\text{SiO}_2})/dz$ shows the slope of the semi-log plot of the growth rate distribution along the flow axis in the diffusion-controlled region. And r , u , and Sh show the radius of the quartz short tube, the average gas flow rate in the

diffusion-controlled region, and the Sherwood number (= 3.66), respectively.

Fig. 5 shows the dependence of the diffusion coefficient on the average wall temperature in the diffusion-controlled region and on the O₂ concentration at about 1260 K. The diffusion coefficient was calculated by using Eq. (7). The keys and lines show the experimental data and the curve-fitting lines of $T_{\text{av}}^{1.75}$, respectively. A power 1.75 of temperature was reported by Fuller *et al.* for polyatomic gas¹⁰⁾.

The diffusion coefficient of $x_{\text{O}_2, \text{init}} = 0.285$ at about 1260 K was lower than that of $x_{\text{O}_2, \text{init}} = 0.089$ and 0.165. As the colors of the substrate are brownish in Fig. 3 i) and ii), adhesion is poor and the film color is greatly different at $x_{\text{O}_2, \text{init}} = 0.089$ and 0.165. Then, we investigated the growth process at $x_{\text{O}_2, \text{init}} = 0.285$ in this study.

It was found that the diffusion coefficient at 1260 K $\leq T_{\text{av}} \leq 1323$ K differed from that at $T_{\text{av}} \geq 1373$ K. Eq. (8) and Eq. (9) show the diffusion coefficients at 1260 K $\leq T_{\text{av}} \leq 1323$ K and at $T_{\text{av}} \geq 1373$ K, respectively.

$$D = 2.46 \times 10^{-10} T_{\text{av}}^{1.75} \quad (1260 \text{ K} \leq T_{\text{av}} \leq 1323 \text{ K}) \quad (8)$$

$$D = 3.61 \times 10^{-10} T_{\text{av}}^{1.75} \quad (T_{\text{av}} \geq 1373 \text{ K}) \quad (9)$$

The widely spaced dashed line and dashed line with narrow intervals show Eq. (8) and Eq. (9), respectively.

The solid line shows Eq. (10) for all temperatures in this study as follows:

$$D = 3.22 \times 10^{-10} T_{\text{av}}^{1.75} \quad (1260 \text{ K} \leq T_{\text{av}} \leq 1423 \text{ K}). \quad (10)$$

Here, we considered the reason that the diffusion coefficient in Eq. (8) was calculated to be smaller than that in Eq. (9). At $T_{\text{av}} \leq 1323$ K, the color of the film on the substrate changed to transparent or transparent white as shown in Fig. 3 (iii) and (iv) as the temperature rose. It was also suggested that the substances produced could change between conditions (iv) and (v). Specifically, it was suggested that the reaction intermediate having a larger molecular

Fig. 5 Diffusion coefficient temperature and O₂ molar fraction dependence

weight than that of the SiO_2 could be generated and deposited at $1260 \text{ K} \leq T_{\text{av}} \leq 1323 \text{ K}$, while SiO_2 with sufficiently advanced thermal decomposition could be generated and deposited at $T_{\text{av}} \geq 1323 \text{ K}$.

Here, the binary diffusion coefficient of components A and B below the atmospheric condition has already been established by the Chapman-Enskog theory, and the diffusion coefficient is expressed by the following Eq. (11)¹¹⁾.

$$D_{\text{AB}} = 0.00018583 \frac{\sqrt{T^3 \left(\frac{1}{M_A} + \frac{1}{M_B} \right)}}{p \sigma_{\text{AB}}^2 \Omega_{\text{AB}}} \quad (11)$$

Here, $p[\text{atm}]$, σ_{AB} , Ω_{AB} , M_A and M_B show the operating pressure, collision radius, collision integral, and molecular

weight of component A and B. In this study, component A and component B show carrier gases of N_2 and remaining O_2 , and the reaction intermediate during CVD or SiO_2 , respectively. If the reaction intermediate having a molecular weight was assumed to be higher than that of SiO_2 deposited at $1260 \text{ K} \leq T_{\text{av}} \leq 1323 \text{ K}$, the diffusion coefficient could become smaller than that of the carrier gas and SiO_2 .

4.4 Comparison of the experimental growth rate with the calculated growth rate

Fig. 6 shows a normal plot of the growth rate distribution of the SiO_2 film along the distance from the heater inlet, z . Plots and lines show the experimental and

Fig. 6 Calculation results of growth rate distribution along the flow axis for the SiO_2 film coating with experimental ones

Fig. 7 SEM images of the quartz tubes after CVD at various setting wall temperatures

calculated results, respectively. The solid line and the broken line show the calculated results using Eq. (10) and Eq. (8) or Eq. (9), respectively. For all conditions, the experimental results could be reproduced by the calculated results before the maximum growth rate when the mass transfer could be controlled by the surface reaction. However, the calculation results disagreed partially with the experimental results after the maximum growth rate when the mass transfer could be controlled by the diffusion. At $T_s = 1273$ K in Fig 6 a), the calculation results of growth rates using Eq. (8) and using Eq. (10) did not agree with the experimental growth rates at $0.1 \text{ m} < z < 0.3 \text{ m}$. However, they did agree using Eq. (10). In Figs. 6 b) and c), calculation results of growth rates using both Eq. (8) or Eq. (9) and using Eq. (10) agreed wholly with the experimental growth rates except for the maximum growth rate. On the other hand, in Figs. 6 d) and e), the calculation results of growth rates using Eq. (9) and using Eq. (10) were higher than that of the experimental growth rates at $0.1 \text{ m} < z < 0.35 \text{ m}$.

4.5 SEM observation of the deposited material on the substrate at the maximum growth rate

In order to investigate the reason that the growth rate could not be reproduced by calculation at $T_s = 1273$ K and $T_s > 1423$ K, SEM observation was conducted. Fig. 7 shows SEM images for the original quartz tube and for the deposited material on the quartz tube at several T_s . A few small particles deposited on the substrate at $T_s = 1273$ K (condition iii). The precise particulate film deposited on the

substrate at $T_s = 1323$ K (condition iv) and at $T_s = 1423$ K (condition vi). On the other hand, at $T_s = 1473$ K (condition vii), the deposited material had not only precise particulate film but also particles of about 40 μm , and the surface morphology was very complex. In comparing these SEM images with the photographs of the substrate as shown in Fig. 3, particles rather than the particulate film could be easily formed when the color of the substrate became white. As particle formation could control mass transfer at $T_s = 1273$ K and $T_s > 1423$ K, the growth rate could not be reproduced by calculation.

Therefore, it was found that the estimated surface reaction rate in this study could be apparent surface reaction rate with no influence of particle formation. It was also suggested that the diffusion coefficient in Fig. 5 could be the apparent diffusion coefficient with the effect of particle formation. In future work, according to the estimation of the particle formation rate by using the membrane filter, the growth rate distribution could be reproduced by numerical calculation with not only surface reaction but also particle formation.

5. Conclusion

This paper investigated the growth rate of SiO_2 solid film on substrates using thermal CVD in a horizontal tubular reactor experimentally and numerically. The following conclusions were obtained.

By using the differential reactor model, the apparent surface reaction rate taking no particle formation into

consideration could be represented by a single correlation line even if the initial mole fraction of O_2 changed. The activation energy of the apparent surface reaction rate constant was 335 kJ/mol.

For all conditions, the experimental results for the growth rate of CVD was reproduced by the calculation ones before the maximum growth rate when the mass transfer could be controlled by the apparent surface reaction. On the other hand, the calculation results for the growth rate of CVD disagreed to some extent with the experimental ones after the maximum growth rate when the mass transfer could be controlled by diffusion of the precursor.

By the observation of SEM images, the mass transfer in this CVD could include not only surface reaction but also particle formation. It was also suggested that the diffusion coefficient could become the apparent coefficient with the effect of particle formation. In future work, according to the estimation of the particle formation rate by using a membrane filter, the growth rate distribution could be reproduced by numerical calculation with not only surface reaction but also particle formation.

Nomenclature

C_{HMDSO}	: Molar concentrations of HMDSO	[mol/m ³]
C_{O_2}	: Molar concentration of O_2	[mol/m ³]
D	: Diffusion coefficient by Akiyama <i>et al.</i> ³⁾	[m ² /s]
D_{AB}	: Diffusion coefficient by Chapman-Enskog theory ¹²⁾	[m ² /s]
$G_{\text{SiO}_2,i}$	: Growth rate of deposited SiO_2 of the i -th quartz tube	[kg/m ² /s]
k_s	: Surface reaction rate constant	[m/s]
M_A	: Molecular weight of A in Eq. (11)	[g/mol]
M_B	: Molecular weight of B in Eq. (11)	[g/mol]
$m_{0,i}$	: Mass of the i th short quartz tube before experiment	[kg]
m_i	: Mass of the i th short quartz tube after experiment	[kg]
M_{SiO_2}	: Molecular weight of SiO_2	[kg/mol]
N_{SiO_2}	: Growth rate obtained using a differential reactor model	[mol/m ² /s]
p	: Operating pressure in Eq. (11)	[atm]
P	: Operating pressure	[Pa]
r	: Radius of the quartz short tube	[m]
R_0	: Universal gas constant (= 8.314 J/mol/K)	[J/mol/K]

S_i	: Inner surface area of the i -th quartz tube	[m ²]
Sh	: Sherwood number	[-]
T_s	: Setting temperature on the outer wall of the tubular reactor which was regulated by the thermostat of the electric furnace	[K]
T_{av}	: Average wall temperature in the diffusion-controlled region	[K]
$T_{IW,i}$	: Wall temperature of the i -th substrate	[K]
u	: Average gas flow rate in the diffusion limited zone	[m/s]
W_0	: Amount of HMDSO supplied	[kg/s]
x_{O_2}	: Oxygen molar fraction	[-]
z	: Distance from heater inlet	[m]

Greek symbol

ΔE	: Activation energy of the surface reaction	[J/mol]
ΔM	: Total mass of deposited SiO_2	[kg]
σ_{AB}	: Collision radius of molecule A and B in Eq. 11	[Å]
Ω_{AB}	: Collision integral in Eq. (11)	[-]

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