Heat and Mass Transfer of Impinging Jet Flow with Shower Head Flow on a Heated Disc in a Cylindrical Flow Channel

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The horizontal temperature measurement on the heated disc in the cylindrical hydrogen flow channel with impinging jet was performed to examine the effect of the non-dimensional distance between the gas inlet and the heated disc ($H_N^*$) and the nozzle Reynolds number ($Re_N$) on the heat transfer in a chemical vapor deposition (CVD) reactor. Furthermore, two dimensional numerical simulation in heat and mass transfer on the heated disc was conducted to predict the growth rate distribution along the $r$-coordinate in the CVD reactor. The less $H_N^*$ created, the lower the experimental temperature at $r^* = 0$ mm because of the impinging jet flow. The calculation temperature along the $r$-coordinate agreed well with the experimental temperature except for $H_N^* = 0.69$ at $r^* = 0$. When the non-dimensional surface reaction rate constant $k^*$ was $3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7} (k = 10^{-6} \text{ m/s})$, the predicted growth rate of the source material on the heated disc decreased exponentially with the $r$-direction because the film formation could proceed under the diffusion rate-determining condition along the radial direction. On the other hand, at the central region the influence of mass transfer due to forced convection discharged from the jet becomes stronger at $0.036 \leq k^* \leq 0.126 (k = 1 \text{ m/s})$ than that at $3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7} (k = 10^{-6} \text{ m/s})$ and the film formation rate is greatly attenuated. The higher the distance from the nozzle to the heated disc $H_N$ got, the smaller the gradient of the growth rate in the $r$-direction at $0 \leq r^* \leq 3.45$ because the mass transfer could be controlled by the surface reaction if the $H_N^*$ increased. The more the $H_N^*$ and the less the reaction rate were constant, the smaller the coefficient of variation of the growth rate. In this study, the minimum coefficient of variation for the growth rate distribution was about 0.41. Therefore, it is suggested that the hybrid supply system of the raw material for chemical vapor deposition from not only impinging jet flow but also shower head flow could be suitable.

Key Words
Impinging jet flow, Shower head flow, Chemical vapor deposition, Diffusion controlled
1. Introduction

Chemical vapor deposition (CVD) is a material synthesis method in which a raw material is supplied in a gas phase to a reactor and a thin film having the desired composition is formed by a chemical reaction in the gas phase or on the substrate surface. The advantage of CVD is that the pressure, reaction temperature, and flow rate can be freely selected. In addition, since there is no restriction on the type and mechanism of the reaction, the types of raw materials that can be used and the types of solids that are formed are numerous, and can be applied to a very wide range of fields.

As a manufacturing method aiming at increasing the diameter of the thin film produced by CVD, plasma generation [3], the resistance-heating of the substrate with high rotating speed [3], the microwave-heating of the substrate [9], and the feeding of raw material by the injection valve [6] and so forth were investigated. Regarding these methods, the radial smoothness of the film formation rate on a substrate from 100 mm to 300 mm in diameter has been discussed using experimental methods and conditions.

In the formation of large-diameter thin films, the important issue is how to make the film formation rate almost uniform, which has been commonly lower at the center of the substrate than that at the edge of it. Impinging jet flow is speculated to be one of the methods to solve the problem, and in recent years, the formation of carbide thin films such as SiC [5]~[9] and B4C has been reported [10].

For impinging jet flow on a substrate of several tens of degrees, flow visualization using smoke has been conducted [11]~[14]. The influence of the wall around the impinging jet has also been investigated [16]. Furthermore, a study of the supply direction (vertically upward or vertically downward) using numerical analysis has also been performed [15]. In recent years, the impinging jet flow velocity distribution by the particle image velocimetry method has been measured when the substrate temperature was 953 K [16], and the flow in the actual CVD equipment has been elucidated.

The uniformity of thin films in CVD equipment using impinging jet flow is mainly designed by numerical calculations [17]~[20]. Two-dimensional analysis has also been conducted in which the wall surface on the entrance side other than the jet is brought closer to the high temperature base [17]~[18], and the high temperature substrate was rotated [17]~[19]. Three-dimensional analysis has also been performed in which raw materials are supplied from the horizontal direction with respect to the rotation of the substrate [20].

On the other hand, numerical analysis on CVD using shower head flow has also been conducted, and research was mainly undertaken to improve the uniformity of thin films by adding substrate rotation [21]~[23]. Furthermore, it was reported that the error between the maximum and minimum film thickness on a wafer with a diameter of 30 cm could be reduced to about 20% when the porous media was installed directly on the substrate with rotation [24].

From these previous studies, in order to achieve the uniform formation rate for CVD along the radial position on large-diameter substrates, it is necessary to utilize the substrate rotation. If it is possible to eliminate the rotation of the substrate and make the film formation rate uniform by the synthesis of the impinging jet flow and the shower head flow, not only can the equipment be simplified but also the cost can be significantly reduced. It is also important to investigate the effect of the supply method of raw material on the uniformity of the film formation rate when the CVD film formation process could be controlled not only by the diffusion of the raw material, but also by the chemical reaction on the substrate surface.

The purpose of this study was to investigate the uniformity of the film formation rate for CVD due to the non-rotation equipment of the impinging jet flow and the shower head flow. Specifically, the horizontal cross-sectional temperature on the high-temperature substrate heated up to 300 °C was measured and compared with two-dimensional heat transfer and fluid flow analysis. Furthermore, we investigated the growth rate distribution by CVD on the heated disc using the numerical simulation. The objective of the CVD simulation was to investigate the dependence of the impinging jet and the shower head flow on the growth rate distribution because there is no data for growth rate experiments using not only the impinging jet but also the shower head flow for the previous reports.

2. Experimental

Fig. 1 shows a schematic diagram of the experimental apparatus on the heated disc. The hydrogen (H₂) gas is fed into the flow channel with the heated disc through the stainless steel pipe. The inner diameter and outer diameter of the pipe were 4.35 mm and 6.35 mm, respectively. In order to reduce the natural convection on the heated disc, another H₂ gas was also fed into the flow channel through the packed bed of the grass beads and perforated plate. These gas flow rates were regulated by the mass flow controllers (Horiba STEC, SEC E40). The ratio of the gas flow rate through the stainless steel pipe was 1% of the total gas flow rate $Q_{i}$ into the flow channel. The three sheath thermocouples with a wire diameter of 1 mm were installed at the tip of the stainless steel pipe and at the tips
of the perforated plate, respectively. The heated disc with a diameter of about 62 mm was made by sandwiching the plate heater between two stainless steel plates. One of the stainless steel plates was connected to a stainless steel tube to support the heated disc. The cylindrical insulator was surrounded by the heated disc to suppress the heat loss from the heater. Another three sheath thermocouples were embedded in the stainless steel plate. The temperature at the center of the heated disc was controlled by the PID controller. The distance from the tip of the stainless-steel nozzle to the heated disc was defined as $H_N$. Nine K-type bare thermocouples with a wire diameter of 100 µm were installed at a position 2 mm above the heated disc. The measurement points of the horizontal cross-sectional temperature were set at 90° intervals on concentric circles with $r = 0, 15,$ and $30$ mm. After the temperature measurements on the heated disc, the temperature at the inlet, at the heated disc, at the inner wall of the flow channel, and at the insulator wall was also measured for the boundary conditions of the numerical simulation. The operation pressure was 101.3 kPa.

### 3. Numerical simulation

Two-dimensional numerical simulation on the heated disc in the cylindrical flow channel in H$_2$- a source material for chemical vapor deposition was conducted. The source material gas was diluted by hydrogen (H$_2$) gas and fed into the flow channel with the heated disc through the stainless-steel pipe. The mole fraction of the source material in the stainless-steel pipe was set at 0 or 0.005. Table 1 shows the

| Table 1 Continuity, Navier-Stokes equation, energy balance and mass balance of source material on the heated disc in the cylindrical flow channel |
|---|
| Continuity | $\frac{1}{r} \frac{\partial}{\partial r} (ru) + \frac{\partial}{\partial z} (w) = 0$ |
| Navier-Stokes (r-direction) | $\frac{1}{r} \frac{\partial}{\partial r} (\rho u u) + \frac{\partial}{\partial z} (\rho u w) = -\frac{\partial}{\partial r} (\rho u) - \frac{1}{r} \frac{\partial}{\partial r} \left( \rho (ru) \right) + \frac{\partial P}{\partial r}$ |
| Navier-Stokes (z-direction) | $\frac{1}{r} \frac{\partial}{\partial r} (\rho u w) + \frac{\partial}{\partial z} (\rho w w) = -\frac{\partial}{\partial z} (\rho w) - \frac{1}{r} \frac{\partial}{\partial r} \left( \rho (ru) \right) + \frac{\partial P}{\partial z}$ |
| Energy balance | $\frac{1}{r} \frac{\partial}{\partial r} \left( \rho C_p u T \right) + \frac{\partial}{\partial z} \left( \rho C_p w T \right) = \frac{1}{r} \frac{\partial}{\partial r} \left( \rho D_{H_2} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \rho D_{H_2} \frac{\partial T}{\partial z} \right)$ |
| Mass balance for Source Material | $\frac{1}{r} \frac{\partial}{\partial r} (\rho y_{H_2} u) + \frac{\partial}{\partial z} (\rho y_{H_2} w) = \frac{1}{r} \frac{\partial}{\partial r} \left( \rho D_{H_2} \frac{\partial y_{H_2}}{\partial r} \right) + \frac{\partial}{\partial z} \left( \rho D_{H_2} \frac{\partial y_{H_2}}{\partial z} \right)$ |
governing equations for the numerical simulation. **Fig. 2** shows the calculation domain and boundary conditions. In this simulation, the growth rate on the heated disc was given as follows if the first order reaction of the source material was assumed.

\[ GR = -\rho D_{SM,0} \frac{\partial y_{SM}}{\partial z} = k \rho y_{SM} \]  

(1)

Where \( k \) [m/s] is the reaction rate constant. In this simulation, the value of \( k \) was selected at 1 m/s and \( 10^{-6} \) m/s.

The governing equations in Table 1 and boundary conditions in Fig. 2 were discretized by the control volume method. The velocity and pressure profiles were decided by the SIMPLE algorithm. Each discretized governing equation with boundary conditions was solved by the THOMAS method. In order to satisfy simultaneously all discretized governing equations and boundary conditions for all grids, the steady state calculation was conducted repeatedly until the relative error at each grid between the expected value and the calculated value for \( u, w, T \) and \( y_{SM} \) was less than or equal to \( 10^{-6} \).

The dependence of all physical properties on the temperature and mole fraction of \( H_2 \) and the source material was taken into account for the simulation. In this case, sulfur hexafluoride (SF\(_6\)) was used as a simulated source material for chemical vapor deposition. Grid sensitivity on the growth rate distribution along the flow axis was investigated using \((M_r, M_z) = (150, 343), (200, 458), (300, 686), \) and \((400, 915)\). Where \( M_r \) and \( M_z \) show the mesh number along the radial component and along the axial component, respectively. The maximum relative error of the growth rate between \((M_r, M_z) = (300, 686)\) and \((M_r, M_z) = (400, 915)\) was about 0.59\%. We investigated also the grid sensitivity for heat transfer without the chemical reaction. The maximum relative error of the temperature between \((M_r, M_z) = (300, 686)\) and \((M_r, M_z) = (400, 915)\) was about 0.2\% for \( H_z = 3 \) mm. Therefore, \((M_r, M_z) = (300, 686)\) was adopted in this simulation.

In this study, heat and mass transfer during chemical vapor deposition were investigated generally using the following non-dimensional parameters.

\[
\begin{align*}
\rho &= \frac{\rho}{\rho_0} \\
D_{SM,0} &= \frac{D_{SM,0}}{D_{H2-SM,0}} \\
T &= \frac{T}{T_0} \\
Re &= \frac{\rho D_{SM,0} \rho H_2 y_{SM,0}}{\mu} \\
GR &= \frac{GR}{\rho D_{SM,0} \rho H_2 y_{SM,0}} \\
k' &= \frac{k \rho H_2 y_{SM,0}}{\rho_0 H_2} \\
\end{align*}
\]  

(2) (3) (4) (5) (6) (7)
Before the experiments, the measured temperature at nozzle inlet $T_0$ changed due to $H_N$ and $Q_T$ as shown in Table 2.

Then nozzle-Reynolds number changed also due to $H_N$ and $Q_T$.

### Table 2 Measured temperature at nozzle inlet, $T_0$ [K]

| $H_N$ [mm] | $Q_T$ [SLM] | 2   | 3.5 | 5   | 7   |
|------------|-------------|-----|-----|-----|-----|
| 3          |             | 385 | 367 | 371 | 360 |
| 5          |             | 419 | 420 | 420 | 418 |
| 10         |             | 430 | 429 | 426 | 420 |
| 20         |             | 430 | 428 | 427 | 420 |

$$H_N^* = \frac{H_N}{d_N} \tag{8}$$

$$y_{SM*} = \frac{y_{SM,in}}{y_{SM,in}} \tag{9}$$

Before the experiments, the measured temperature at nozzle inlet $T_0$ changed due to $H_N$ and $Q_T$ as shown in Table 2. Then nozzle-Reynolds number changed also due to $H_N$ and $Q_T$.

### Results and discussion

#### 4.1 Temperature measurements on the heated disc and comparison with the calculation

Fig. 3 shows the non-dimensional temperature distribution along the $r$-coordinate at $z^* = 4.14$. The inlet mass fraction in the stainless steel pipe $y_{SM,in}$ was equal to 0. The plots and lines show the experimental and calculation results, respectively. In Fig. 3a) the experimental temperature decreased with the $r$-coordinate. The less $H_N^*$ created, the lower the temperature at $r^* = 0$ as shown in Fig. 3b), c), and d) because of the impinging jet flow. These tendencies did not change when the nozzle-Reynolds number $Re_N$ was 1.07 in Fig. 3e), f), and g). However, in Fig. 3h) the experimental temperature at $r^* = 0$ for $H_N^* = 0.69$ was higher than that at $r^* = 3.45$ and 6.9. The calculation temperature agreed well with the experimental one for $H_N^* = 1.15, 2.30$ and 4.60. The non-dimensional maximum error between the experimental temperature and the calculation one was 0.058 ($=24.4$ K) at $r^* = 0$ for $H_N^* = 1.15$ and $Re_N = 3.76$. On the other hand, the experimental temperature was much lower than calculation one at $r^* = 0$ for d) $H_N^* = 0.69$ and $Re_N = 4.15$ and h) $H_N^* = 0.69$ and $Re_N = 1.13$. In these conditions, the K type bare thermocouple was almost on the heated disc due to the impinging jet after the experiments. As written in Section 3, the dependence of the calculation

![Fig. 3 Comparison of the calculation temperature distribution at $z^* = 4.14$ along the $r$-coordinate on the heated disc with the experimental types. ($y_{SM,in} = 0$)](image-url)
temperature on the grid sensibility was less than 0.2 %. Then it suggested that the experimental temperature at \( r^* = 0 \) for these conditions could measure at the different position along the \( z \)-coordinate. Therefore, heat and mass transfer on the heated disc were investigated except for \( H_0^* = 0.69 \) in this study.

4.2 Heat and mass transfer in \( \text{H}_2 \)-dilute source material system on the heated disc in the cylindrical flow channel

Fig. 4 shows the calculation results of heat and mass transfer in the \( \text{H}_2 \)-dilute source material on the heated disc in the cylindrical flow channel. The nozzle-Reynolds number and non-dimensional distance between the tip of the stainless-steel pipe and the heated disc were \( Re_N = 2.68 \) and \( H^* = 1.15 \), respectively. The inlet mass fraction in the stainless-steel pipe, \( \gamma_{SM, in} \), was equal to 0.27. The non-dimensional reaction rate constant \( k^* \) was 0.05. The contour maps of the left-hand side and the right-hand side show the temperature and velocity vector distributions and mass fraction of the source material, respectively.

In this case, the 0.05 SLM of hydrogen (\( \text{H}_2 \)) with 27 mass\% source material was fed into the flow channel through the stainless-steel pipe. The 4.95 SLM of hydrogen gas was also fed into the flow channel outside of the stainless-steel pipe. From the contour map on the left-hand side, the temperature distribution on the heated disc was suppressed by the material on the heated disc along the cylindrical flow channel. \( \text{H}_2 \)-source material flow from the stainless-steel pipe. The source material gas diffused along the \( r \)-coordinate as shown in the contour map on the right-hand side.

Fig. 5 shows the semi-log plot of the growth rate distribution along the \( r \)-coordinate on the heated disc. In Fig. 5 a), at \( H_0^* = 1.15 \), \( k^* = 1.27 \times 10^7 \), and \( Re_N = 107 \), the non-dimensional growth rate of the source material at the center (\( r^* = 0 \)) was about 0.23 and decreased exponentially with the \( r \)-direction. Akiyama reported that the growth rate in the tube-type CVD reactor decreases exponentially in the flow axial direction if the mass transfer rate was controlled by the diffusion of the source material\(^\text{25} \). Although this analysis system for \( 3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7} \) (\( k = 10^{-6} \text{ m/s} \)) is different from that of Akiyama’s results\(^\text{25} \), it is suggested that the film formation could proceed under the diffusion-rate-determining condition along the radial direction. The growth rate increased with the total gas flow rate due to the forced convection. On the other hand, the growth rate for \( 0.036 \leq k^* \leq 0.126 \) (\( k = 1 \text{ m/s} \)) was naturally higher than that for \( 3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7} \) and its distribution was divided by \( 0 \leq r^* \leq 3.45 \) and at \( r^* > 3.45 \). When the reaction rate constant is \( 0.036 \leq k^* \leq 0.126 \), \( k^* \leq 0.126 \), at \( 0 \leq r^* \leq 3.45 \) the influence of mass transfer due to forced convection discharged from the jet becomes stronger and the film formation rate is greatly attenuated. The gradient of the growth rate in the \( r \)-direction was close to that at \( 3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7} \). Although the growth rate increased with the total gas flow rate due to the forced convection, the tendency of the growth rate distribution did not change. In Fig. 5 b) at \( Re_N = 2.68 \) and \( 3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7} \), the higher the distance from the nozzle to the heated disc \( H_N^* \) got, the smaller the gradient of the growth rate in the \( r \)-direction at \( 0 \leq r^* \leq 3.45 \). The mass transfer could be controlled by the surface reaction if the \( H_N^* \) increased. At \( r^* > 3.45 \), the gradient of the growth rate in the \( r \)-direction was close to that for the diffusion-controlled. These tendencies were the same as that at \( 0.036 \leq k^* \leq 0.126 \).

Fig. 6 shows the dependence of the average growth rate along the \( r \)-direction and its coefficient of variation for growth rate distribution along the \( r \)-direction on the nozzle-Reynolds number \( Re_N \) and the non-dimensional distance from the tip of the stainless-steel nozzle to the heated disc \( H_N^* \). The average non-dimensional growth rate and the coefficient of variation of it were given by,
Where $M_{r,D}$ shows the grid number along the $r$-direction at the edge of the heated disc.

In Fig. 6 a) at $3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7}$ ($k = 10^{-6} \text{ m/s}$) and $H_N^* = 4.6$ the average growth rate increased linearly with the nozzle-Reynolds number $Re_N$. However for $H_N^* = 1.15$ the average growth rate increased with the $Re_N$ and then approached a certain growth rate. This could be because the film deposited only on the central region along the $r$-direction for lower $H_N^*$ and higher $Re_N$. On the other hand, in Fig. 6 b) at $0.036 \leq k^* \leq 0.126$ ($k = 1 \text{ m/s}$) the average growth rate increased linearly with nozzle-Reynolds number $Re_N$ for all $H_N^*$. In Fig. 6 c) and 6d the coefficient of variation for the growth rate distribution hardly changed with $Re_N$ at $3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7}$ and $0.036 \leq k^* \leq 0.126$. In Fig. 6 c) and 6 d), the more the $H_N^*$ and the less the reaction rate had the smaller the coefficient of variation. In this study, the minimum coefficient of variation for the growth rate distribution was about 0.41.

The growth rate at the central region along the $r$-direction could be increased by the combination of impinging jet flow and shower head flow. However, the growth rate had a variation which was about 40% of the average one if a suitable condition could be applied. It is suggested that the hybrid supply system of the raw material for chemical vapor deposition from not only impinging jet flow, but also shower head flow could be suitable.

In the future work, we will investigate the CVD experiments using impinging jet and the shower head flow and the validity of this CVD simulation by comparing with the experimental results.

5. Conclusions

In this paper, the horizontal temperature measurement on the heated disc in the cylindrical hydrogen flow channel with impinging jet was performed to examine the effect of the non-dimensional distance from the tip of the stainless-steel nozzle to the heated disc ($H_N^*$) and the nozzle Reynolds number ($Re_N$) on the heat transfer in the chemical vapor deposition (CVD) reactor. Furthermore, two dimensional numerical simulation in heat and mass transfer on the heated disc was conducted to predict the growth rate distribution along the $r$-coordinate in the CVD reactor. The following conclusions were obtained.
The less $H_N^*$ created, the lower the experimental temperature at $r^* = 0$ because of the impinging jet flow for $Re_N = 1.07$ and 3.76. The calculation temperature along the $r$-coordinate agreed well with the experimental one except for $H_N^* = 0.69$ at $r^* = 0$ because the K-type bare thermocouple at $r^* = 0$ on the heated disc could be very close to the heated wall by the impinging jet gas.

When the non-dimensional surface reaction rate constant $k^*$ was $3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7}$ ($k = 10^{-6}$ m/s), the predicted growth rate of the source material on the heated disc decreased exponentially with the $r$-direction because the film formation could proceed under the diffusion rate-determining condition along the radial direction. On the other hand, the growth rate at $0.036 \leq k^* \leq 0.126$ ($k = 1$ m/s) was naturally higher than that at $3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7}$ ($k = 10^{-6}$ m/s) and its distribution was divided by $0 \leq r^* \leq 3.45$ and at $r^* > 3.45$. When the non-dimensional reaction rate constant is $0.036 \leq k^* \leq 0.126$, at $0 \leq r^* \leq 3.45$ the influence of mass transfer due to forced convection discharged from the jet becomes stronger and the film formation rate is greatly attenuated.

The higher the non-dimensional distance from the nozzle to the heated disc $H_N^*$ got, the smaller the gradient of the growth rate in the $r$-direction at $0 \leq r^* \leq 3.45$. The mass transfer could be controlled by the surface reaction if the $H_N^*$ increased. At $r^* > 3.45$ the gradient of the growth rate in the $r$-direction was close to that for the diffusion-controlled. These tendencies were the same as that at $0.036 \leq k^* \leq 0.126$.

At $3.60 \times 10^{-9} \leq k^* \leq 1.27 \times 10^{-7}$ and $H_N^* = 4.60$ the average growth rate increased linearly with the nozzle Reynolds number $Re_N$. However at $H_N^* = 1.15$ the average growth rate increased with the $Re_N$ and then approached a certain growth rate. This could be because the film deposited only on the central region along the $r$-direction for lower $H_N^*$ and higher $Re_N$.

The coefficient of variation for the growth rate distribution hardly changed with $Re_N$ even if the reaction rate constant was changed. The more the $H_N^*$ and the less the reaction rate were constant, the smaller the coefficient of variation of the growth rate. In this study, the minimum coefficient of variation for the growth rate distribution was
about 0.41. Therefore, it is suggested that the hybrid supply system of the raw material for chemical vapor deposition from not only impinging jet flow, but also shower head flow could be suitable.

Nomenclature

\( C_p \) : Specific heat [J/kgK]
\( D_{12,\text{mat}} \) : Diffusion coefficient of hydrogen and source material [m²/s]
\( D_{12,\text{mat}}(T) \) : Diffusion coefficient of hydrogen and source material at \( T \) [m²/s]
\( d_n \) : Nozzle inner diameter (= 0.00435 m) [m]
\( k \) : Surface reaction rate constant [m/s]
\( k^* \) : Non-dimensional surface reaction rate constant defined by Equation (7)[-]
\( M_r \) : Grid number for \( r \)-coordinate [-]
\( M_{r,0} \) : Grid number for \( r \)-coordinate at edge of the heated disc [-]
\( M_z \) : Grid number for \( z \)-coordinate [-]
\( g \) : Gravity acceleration (= 9.80665 m²/s) [m/s²]
\( GR \) : Growth rate on the heated disc [kg/m²s]
\( GR^* \) : Non-dimensional growth rate on the heated disc defined by Equation (6) [-]
\( H_s \) : Distance from tip of the stainless-steel nozzle to the heated disc [mm]
\( H_s^* \) : Non-dimensional distance from tip of the stainless-steel nozzle to the heated disc defined by Equation (8) [-]
\( \rho \) : Density [kg/m³]
\( \rho_0 \) : Density at the nozzle inlet [kg/m³]
\( \lambda \) : Thermal conductivity [W/m K]
\( \gamma \) : Shear stress [Pa]
\( \zeta \) : Coefficient of variation for growth rate distribution [-]

Greek Symbol

\( \nu \) : Velocity of \( r \)-component [m/s]
\( \nu_{n,0} \) : Velocity of \( r \)-component at nozzle inlet [m/s]
\( w \) : Velocity of \( z \)-component [m/s]
\( \phi_{\text{mat}} \) : Mass fraction of source material [-]
\( \phi_{\text{mat},0} \) : Mass fraction of source material at nozzle inlet [-]
\( z \) : Axial position of the flow channel [m]
\( z^* \) : Non-dimensional axial position of the flow channel defined by Equation (9) [-]

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