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ABSTRACT
A regional control constrained spray deposition model was established to study the flow fields and deposition of atomized droplets in a semienclosed space. The FLUENT software was used to simulate the changing rules of the pressure field, velocity field, and temperature field under different atomization gas pressures (AGPs), aiming to optimize the equipment and parameters of spray Conform. The results show that the flow fields are prone to be disturbed by the controller of the two rotating disks when the AGP is low, which makes it difficult to control the droplet deposition. Besides, excessive AGP will bring a robust reverse airflow, which is not conducive to control droplet deposition either. However, the outlet pressure of the diversion tube is about 2.5 × 10^4 Pa when the AGP is between 2.5 and 3.0 × 10^5 Pa. In this condition, the melt will exit the nozzle without blockage. Moreover, the pressure near the basement is about 5 × 10^4 Pa at this point, making the droplet deposition controllable.

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I. INTRODUCTION
To solve the problems of energy waste and process complexity caused by reheating and densification of porous billets prepared by spray forming, a short-process composite technology of Spray Conform (SC) was proposed. The SC technology combines spray forming with Conform technology directly. The principle is that the alloy melt is atomized first, then deposited into the groove of the extrusion wheel under the constraint of the controller, and finally formed by continuous extrusion,

Regional control constrained spray deposition (RCCSD) is a newly proposed technology based on spray deposition. For providing suitable billets with appropriate shape and size for direct continuous processing, the atomized droplets must be constrained by a controller to deposit in a specific area with a particular form. In SC, the extrusion wheel groove with 10–30 mm width and 15–35 mm depth is the basement. The shape and size of the deposited billets must match the cellar. RCCSD is the basis of the SC technology. The spray atomization is restrained by symmetrically assembling a pair of high-speed rotating disks. SC is a near-net-shape manufacturing technology from liquid to the finished product directly. It has the advantages of rapid solidification, extensive plastic deformation, and continuity. Expressly, the segregation of alloy elements is restrained due to the fast crystallization of droplets at the atomization stage, thus improving the homogeneity of the composition. The useful nucleation quantity is increased by reducing the critical crystal nucleus size due to rapid cooling, so the grain size is refined. Moreover, the deposited billet is then further improved, and the density is increased by continuous angular extrusion.

Regional control constrained spray deposition (RCCSD) is a newly proposed technology based on spray deposition. For providing suitable billets with appropriate shape and size for direct continuous processing, the atomized droplets must be constrained by a controller to deposit in a specific area with a particular form. In SC, the extrusion wheel groove with 10–30 mm width and 15–35 mm depth is the basement. The shape and size of the deposited billets must match the cellar. RCCSD is the basis of the SC technology. The spray atomization is restrained by symmetrically assembling a pair of high-speed rotating disks under the exit of the atomizer nozzle. Also, the fly direction of the metal droplets is controlled by the rotating disks. The droplets fly out from the lower edges of the disks and deposit in the groove basement. Then, the billets will be extruded continuously under hot condition. However, the controller of the high-speed rotating disks interferes significantly with the flow fields during atomization, which makes the pressure field (PF), velocity field (VF), and temperature field (TF) complicated. Furthermore,
FIG. 1. Schematic of the spray Conform technique.

the turbulent airflow makes it challenging to deposit droplets in a small basement. So, it is necessary to understand the changing rules of the flow fields. However, it is challenging to study the regulations through experiments.

Therefore, the fluid dynamics software of FLUENT is used to simulate the PF, VF, and TF of RCCSD in SC. The simulation results are verified by experiments. This work can provide a theoretical basis for the design of an atomizer, the optimization of parameters, the development of SC, and the extension of spray forming.

II. SIMULATION METHOD AND BOUNDARY CONDITIONS

A. Control equation

The fluid dynamics governing equation is the basis for solving fluid mechanics. It assumes the fluid as an infinitely separable continuum in time and space. The space occupied by the vapor is called the flow field. The fluid mass is assumed as a macroscopically infinitely small and microscopically infinitely large research unit.

Numerical simulation of the flow fields is based on the conservation equations for mass, momentum, and energy. As for RCCSD flow fields, the ideal gas law, that is, the relationship among temperature, pressure, and density, is also involved in this model.\textsuperscript{9-11}

The continuity equation used in the calculation can be described as follows:

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_i}(pu) = S_m, \tag{1}
\]

where \( p \) is the droplet density, \( t \) is time, \( x_i \) is the droplet coordinate, \( u_i \) is the velocity, and \( S_m \) is the mass of discrete liquid in continuous gas. As for the axisymmetric configuration, Eq. (1) can also be written as

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}(pu) + \frac{\partial}{\partial r}(pv) = S_m, \tag{2}
\]

where \( u \) is the axial velocity, \( v \) is the radial velocity, \( x \) is the axial coordinate, and \( r \) is the radial coordinate.

The energy conservation equation of the model is described as follows:

\[
\frac{\partial (puh)}{\partial x_i} = u_j \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( k_{eff} \frac{\partial h}{\partial x_j} \right) + \Phi, \tag{3}
\]

where \( \Phi \) is the viscous dissipation function. Concretely, after the dependent variable and exchange coefficient under consideration, Eq. (3) can be written as

\[
\frac{\partial}{\partial x_i} \left[ \rho \left( \frac{h}{\rho} + \frac{\mu^2}{2} \right) \right] + \frac{\partial}{\partial x_j} \left[ u_i \rho \left( \frac{h}{\rho} + \frac{\mu^2}{2} \right) + p \right] = \frac{\partial}{\partial x_i} \left[ k_{eff} \frac{\partial T}{\partial x_i} \right] - \sum_l h_f I_f + u_i (\tau_0)_{eff} + S_h, \tag{4}
\]

where \( p \) is the hydrostatic pressure, \( \rho \) is the droplet density, \( \mu \) is the viscous coefficient, \( h \) is the head height, \( k_{eff} \) is the effective heat conductivity, \( I_f \) is the component diffusion flux, and \( \tau_0 \) is the stress tensor. The first three terms on the right side of the equation represent the energy flux caused by heat conduction, component diffusion, and viscous dissipation, respectively. \( S_h \) includes reaction heat and other volume heat.

The momentum equation involved in this model is shown as follows:

\[
\frac{\partial}{\partial x_i} (pu u_i) = -\frac{\partial p}{\partial x_i} + \frac{1}{r} \frac{\partial}{\partial r} \left[ \frac{1}{\rho} \left( r \mu u u_i \right) \right], \tag{5}
\]

where \( x_i \) is the coordinate, \( u_i \) or \( u_j \) is the velocity, \( p \) is the static pressure, and \( \mu_{eff} \) is the effective viscosity. For two-dimensional axisymmetric geometry, Eq. (5) can also be written as Eq. (6) (axial direction) and Eq. (7) (radial direction).

\[
\frac{\partial}{\partial t} (pu) + 1 \frac{\partial}{\partial r} (rpu u_i) + 1 \frac{\partial}{\partial r} (rpu v) \nonumber \\
= -\frac{\partial p}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{1}{\rho} \left( r \mu \frac{\partial u}{\partial x} \frac{2 \frac{\partial u}{\partial x} + \frac{\partial v}{\partial r} + v}{3} \right) \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{2 \frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}}{r} \right) + F_S, \tag{6}
\]

FIG. 2. Structure of the atomizer.
and swirling flow in the spray chamber fitted with a rotating disk when compared with three other turbulence models, i.e., standard \(k-\varepsilon\), realizable \(k-\varepsilon\), and Reynolds stress models using the FLUENT code.\(^{12,13}\)

For the RCCSD model, the flow fields are very complex under the action of two rotating disks. Thus, The RNG \(k-\varepsilon\) turbulence model was selected in this study. The turbulent kinetic energy \(k\) and its dissipation rate \(\varepsilon\) equations of the RNG model are, respectively, given as

\[
\frac{\partial k}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i k\right) = \frac{\partial}{\partial x_i}\left(\frac{\mu}{\sigma_k} \frac{\partial k}{\partial x_i}\right) + \frac{\varepsilon}{\varepsilon} + G_k - \rho \varepsilon - Y_M + F_r, \tag{8}
\]

\[
\frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i \varepsilon\right) = \frac{\partial}{\partial x_i}\left(\frac{\mu}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i}\right) + C_{1\varepsilon} \frac{\varepsilon}{k} \left(G_k - C_{\varepsilon} G_{\varepsilon}\right) - C_{2\varepsilon} \rho \varepsilon^2 + R, \tag{9}
\]

where \(G_k\) and \(G_{\varepsilon}\) are the turbulent kinetic energies owing to the average velocity gradients and buoyancy, respectively; \(Y_M\) represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate; \(C_{1\varepsilon}, C_{2\varepsilon},\) and \(C_{\varepsilon}\) are constants; \(R\) (gas constant) is defined according to the real flow field; and \(a_k\) and \(a_{\varepsilon}\) are the reciprocal of the turbulent Prandtl number for \(k\) and \(\varepsilon\).\(^{10,14}\)

The DPM breakup model is used to track the change in droplet trajectory, showing the exchanging rule of heat, mass, and momentum between discrete and continuous phases.\(^{15}\) The momentum change of droplets satisfies

\[
F = \sum \left[\frac{18\beta \rho_{\text{C}} Re}{24 \pi d^2} (u_d - u_g) + F_{\text{other}}\right] m_d \Delta t, \tag{10}
\]

where \(C_D\) is the drag coefficient; \(Re\) is the relative Reynolds number; \(\rho_{\text{d}}, d,\) and \(u_d\) are the droplet density, diameter, and velocity, respectively; \(u_g\) is the gas flow velocity; \(F_{\text{other}}\) is other interphase force; \(m_d\) is the droplet mass flow rate; and \(\Delta t\) is the time step.

### TABLE II. Boundary conditions.

| Boundary conditions                              | Units | Value |
|--------------------------------------------------|-------|-------|
| In-wall temperature of the funnel                | K     | 1 053 |
| Rate of heat flow                                | W/m³  | 20 000|
| Rotational speeds of double disks                | rpm   | 1 500 |
| Ambient pressure                                 | Pa    | 0     |
| Rotational speeds of the extrusion wheel         | rpm   | 0     |

### TABLE III. Physical properties of \(N_2\) and 7075 Al alloy.

| Properties                                      | Units | \(N_2\) | 7075   |
|-------------------------------------------------|-------|---------|--------|
| Density (liquid)                                | kg/m³ | 1.138   | 2820   |
| \(C_p\) [specific heat (liquid)]                | J/(kg k) | 1040.67 | 960    |
| Thermal conductivity (liquid)                   | w/(m k) | 0.0242  | 0.01   |
| Viscosity (liquid)                              | kg/(m s) | 1.663 \times 10^{-5} | 0.001 |
| Injection temperature                           | K     | ...    | 1023   |
| Molecular weight                                | g/mol | 28.0134 | ...    |

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**B. Computational model**

In FLUENT, the RNG \(k-\varepsilon\) model has been broadly used in turbulent supersonic flows, and the reliability has been validated in many such kinds of simulations.\(^{10}\) Huang et al. showed that the RNG \(k-\varepsilon\) turbulence model is suitable for simulating the complex trajectory, showing the exchanging rule of heat, mass, and momentum between discrete and continuous phases.\(^{15}\) The momentum change of droplets satisfies

\[
F = \sum \left[\frac{18\beta \rho_{\text{C}} Re}{24 \pi d^2} (u_d - u_g) + F_{\text{other}}\right] m_d \Delta t, \tag{10}
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where \(C_D\) is the drag coefficient; \(Re\) is the relative Reynolds number; \(\rho_{\text{d}}, d,\) and \(u_d\) are the droplet density, diameter, and velocity, respectively; \(u_g\) is the gas flow velocity; \(F_{\text{other}}\) is other interphase force; \(m_d\) is the droplet mass flow rate; and \(\Delta t\) is the time step.

**TABLE I. Mesh statistics.**

| Zones of model          | Numbers of mesh |
|-------------------------|------------------|
| Total elements          | 759 198          |
| Total nodes             | 133 009          |
| Spray nozzle            | 37 655           |
| Gas chamber             | 64 028           |
| Pressure inlet (metal)  | 688              |
| Pressure inlet (gas)    | 2 383            |
| Wall-in (metal)         | 4 938            |
| Wall-in (gas)           | 596              |
| Wall                    | 6 079            |
| Disk 1                  | 10 410           |
| Disk 2                  | 10 649           |
| Pressure out            | 25 223           |
| Arc surface             | 2 536            |

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**FIG. 3. Computational mesh for the annular-slit atomizer.**

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**TABLE II. Boundary conditions.**

| Boundary conditions              | Units | Value |
|----------------------------------|-------|-------|
| In-wall temperature of the funnel| K     | 1 053 |
| Rate of heat flow                | W/m³  | 20 000|
| Rotational speeds of double disks| rpm   | 1 500 |
| Ambient pressure                 | Pa    | 0     |
| Rotational speeds of the extrusion wheel| rpm | 0     |
The previous equations can be transformed into the form of a generalized transport equation, which includes the diffusion term, convection term, and source term. Then, a general solution procedure based on the SIMPLE algorithm is applied to solve all the governing equations.\textsuperscript{16,17} Also, the TAB (Taylor Analogy Breakup)\textsuperscript{18} model is chosen as the secondary breakup model, which is one of the most widely used models for calculating spray atomization from oscillation and fragmentation.

FIG. 4. The PFs on the axial symmetrical section of the double disks under different AGPs: (a) $2.0 \times 10^5$ Pa, (b) $2.5 \times 10^5$ Pa, (c) $3 \times 10^5$ Pa, (d) $3.5 \times 10^5$ Pa, and (e) $4.0 \times 10^5$ Pa.
C. Nozzle structure and mesh generation

The structure of the atomizer of the circular annular slot is shown in Fig. 2. The overall height $H$ of the atomizer is 60 mm, the internal height $h_0$ of the gas chamber is 30 mm, the width $d_1$ of the circular annular slot is 1.2 mm, the angle $\alpha$ of the circular annular slot is 25°, the inlet diameter $d_2$ is 70 mm, and the outlet diameter $d_3$ is 4 mm.

The computational domain of confined spray atomization is shown in Fig. 3. It is a coupling body of a cylinder with an extrusion wheel and a rotating mass of a double disk edge jet. Among them, the diameter and height of the cylinder are 400 and 300 mm, respectively; the diameter of the disks is 250 mm; the distance between the disks and the wheel is 10 mm; and the inclination angle between the two drives is $8^\circ$.

The computation domain meshes of irregular triangular are generated by the software of Gambit. The mesh independence of the system is analyzed, and a reasonable method of mesh division is adopted, as shown in Table I. Fine mesh is used to capture the characteristics of the boundary layer, considering the complexity of the nozzle outlet zone. However, in other parts, the coarse mesh is adopted. The acceptability of the mesh generation and iteration time is checked automatically by FLUENT and is also verified from the residual list of the computation with the default setting.

D. Boundary conditions

To simplify the atomization process, according to the Bernoulli equation,

$$p + \frac{1}{2}\rho v^2 + \rho gh = C,$$

(11)

the following assumptions are made: (1) the gas is ideal compressible, (2) the metal melt is an incompressible viscous fluid, (3) the atomized droplets move in a straight line under the action of gravity and airflow, and (4) the droplets are spherical. 19,20 In the formula, $p$, $\rho$, and $v$ are the pressure, density, and velocity of the fluid, respectively; $h$ is the height relative to the selected datum level; and $C$ is the constant.

The boundary conditions are shown in Table II. Besides, the melt inlet is the pressure inlet, the gas inlet is the pressure inlet, the bottom outlet is the pressure outlet, and other wall conditions adopt the standard wall function.

In this study, 7075 aluminum alloy was selected as the metal and $N_2$ was selected as the atomizing gas. Five pressures of $2.0 \times 10^5$ Pa, $2.5 \times 10^5$ Pa, $3.0 \times 10^5$ Pa, $3.5 \times 10^5$ Pa, and $4.0 \times 10^5$ Pa were simulated. The physical properties of $N_2$ and 7075 are shown in Table III.

III. RESULTS AND ANALYSIS

A. Effect of AGP on PF

Figure 4 shows the PFs on the axisymmetric cross section of the double disks under different AGPs. In general, the relationship between total pressure and AGP is positive. The change in PFs is mainly reflected in the vicinity of the axis of the diversion tube. Due to the interference of the rotating double disks, the airflow diverges faster and wider when it reaches the basement. The pressure gradient shows that with the increase in the AGP, the influence of the twin disks on the pressure near the axis decreases first, then increases, and then decreases gradually. The air velocity is slow and easy to diverge under the interference of the disks when the AGP is small. However, the interference would be small due to the high velocity of airflow when the AGP is large. In this condition, the airflow reaches the basement in a more convergent form.

The PFs along the axis of the diversion tube are shown in Fig. 5. The pressure decreases first, then increases, then decreases, and finally increases with the increase in the axial distance. In the range of 0–12.5 mm, the pressure decreases rapidly with the distance increasing and reaches a minimum at about 12.5 mm. The value is inversely related to the AGP. In this region, the pressure is negative, which makes a suction on the melt. Also, the higher the AGP, the stronger the suction. In the range of 12.5–25 mm, the pressure increases rapidly with the distance increasing and reaching the maximum at about 25 mm. The magnitude of the pressure corresponds positively with the AGP. As the distance increases further (75–200 mm), the pressure begins to decrease gradually. The area is between the double disks. The airflow disturbance increases with the increase in AGP. When the distance is close to the base (250–260 mm), the pressure rises rapidly and is proportional to the AGP. The rebounded airflow converges with the atomized gas at the lower edge of the disks, maximizing the gas pressure which is not conducive to deposition. When crossing the lower edge of the disks (>260 mm), the pressure decreases for the space released.

Therefore, the AGP of RCCSD is neither too large nor small. When the AGP is low, the atomization ability is weak, and the PF is susceptible to the double disk interference. Furthermore, the transverse flow is strengthened, leading to the poor controllability of droplets. However, when the AGP is high, the reverse flow is strengthened, which is also not conducive to controlling deposition.

B. Effect of AGP on VF

Figure 6 shows the VFs on the axisymmetric cross section of the double disks under different AGPs. It can be seen that the
velocity is positively related to the AGP, and the variation of VF mainly concentrates in the area directly below the nozzle. The fluctuation of VF is different in different positions. The VF tends to one side near the nozzle and the other near the base because the linear velocity of the upper part and the lower part is opposite when the two disks are rotating. The upper part pushes the airflow to one side, while the lower part pushes to the other side. In the central part of the computational area, the velocity decreases because the linear velocity

FIG. 6. The VFs of the axial symmetrical section of the double disks under different AGPs: (a) $2.0 \times 10^5$ Pa, (b) $2.5 \times 10^5$ Pa, (c) $3 \times 10^5$ Pa, (d) $3.5 \times 10^5$ Pa, and (e) $4.0 \times 10^5$ Pa.
of the disks is small, which makes a smaller influence on the gas flow. Thus, the velocity decreases naturally. In the vicinity of the edge of the disks, the linear velocity is higher, which has a greater impact on the airflow.

The VF along the axis of the diversion tube is shown in Fig. 7. The variation trends of velocity and pressure are similar. In relatively open space, the gas velocity mainly comes from its energy, and the AGP is the decisive factor. The velocity increases with increasing AGP.

The velocity increases with increasing AGP when it is larger \( (>3.0 \times 10^5 \text{ Pa}) \) with the axial distance of 0–13 mm, while the velocity increases first and then decreases at lower pressure \( (<3.0 \times 10^5 \text{ Pa}) \). It is directly related to the turbulence. The velocity stagnation point forms between the axial distance of 13 and 20 mm. The location, number, and value of the point are affected by the AGP. The velocity stagnation points appear at the location of about 13 mm and 20 mm, respectively, when the AGP is less than \( 3.0 \times 10^5 \text{ Pa} \). The two velocity stagnation points are related to the gas turbulence. At the location of about 13 mm in the negative pressure zone, a stagnation point generates due to the convergence of upward vortex and reverse flow. The stagnation point is closer to the nozzle. However, only a velocity stagnation point forms at about 20 mm when the AGP is not less than \( 3.0 \times 10^5 \text{ Pa} \). It can be seen that the stationary point velocities are all greater than 100 m/s, which is in contradiction with the traditional values approaching zero. It is due to the strong interference of the high-speed rotating double disks on the airflow so that the airflow has been in the state of high-speed. When the axial distance is about 35 mm, the gas flow intersects and the velocity reaches the maximum and increases with the increase in the AGP. The liquid metal should be completely broken here. The bigger the airflow velocity, the more sufficient the breaking. However, excessive airflow can easily make droplets fly out of the confinement area, which is not conducive to the control of the deposition of droplets. When the axial distance is greater than 35 mm, the changing trend of VF is consistent with PF. In the position where the speed of the disks is low, the energy transferred to the airflow is small, so the gas speed is low. While in the position where the speed of the disks is high, the energy transferred to the airflow is large, so the gas speed is high.

Figure 8 shows the velocity vectors under different AGPs. From the overall calculation area, the velocity near the axis of the diversion tube is the highest and directed toward the deposited basement. It is shown that the atomized droplets can be deposited into the extrusion groove through the space between the two disks under the constraint. From the enlarged picture near the nozzle, it can be seen that the turbulence appears around the outlet of the diversion tube, and the degree increases with the increase in AGP. The turbulence region is negative, which is the basis of spray forming. The negative region will disappear if the upward airflow compensates for this negative pressure. If so, the metal melt can only flow out by gravity, leading to a small outflow velocity. Furthermore, the melt is prone to solidify in the diversion tube and cause blockage due to the strong cooling ability of the atomized gas which can quickly take the heat of melt at the outlet of the diversion tube away. However, if the pressure is greater than the gravity pressure generated by the melt height, the metal will flow backwards, namely, back-injection. Therefore, the higher AGP is beneficial to obtain larger negative pressure which makes melt outflow more smooth.

**C. Effect of AGP on TF**

Figure 9 shows the TFs at different AGPs. The high-speed rotating disks make the temperature diffuse faster and farther, basically involving the whole calculation area. In the middle and lower parts of the disks, the TFs are biased to one side, which is similar to the PFs and VFs.

The variations of the TFs on the axis of the diversion tube under different AGPs are shown in Fig. 10. After the melt flows out of the diversion tube, the temperature drops rapidly after a short stay and then tends to be flat. In the whole process of atomization, the lost heat accounts for about 62% of the total heat. The smaller AGP keeps the negative pressure zone at a higher temperature, which is conducive to the melt outflow. However, the larger AGP keeps the negative pressure zone at a lower temperature, which makes the melt solidify easily in the diversion tube. However, as mentioned above, the larger AGP is favorable for obtaining greater negative pressure which is advantageous to suck out the melt. Therefore, the influence of AGP on melt outflow should be considered in combination with PF and TF.

In the range of 0–13 mm, the heat dissipation ability is closely related to the AGP. Low pressure brings weak cooling, but high pressure brings strong heat dissipation. So, the outlet of the diversion tube is at a lower temperature when the AGP is higher. At about 13 mm, the temperature drops rapidly because the melt is atomized into droplets. The specific surface area increases rapidly, leading to a quick heat dissipation. On the other side, the melt has been atomized before reaching the intersection under the action of the turbulent airflow. It is different from traditional atomization. The position of the atomization point can be controlled by adjusting the nozzle angle to improve the atomization ability. The temperature tends to be gentle when the axial distance is more than 13 mm. Afterwards, about 38% of the total heat is retained when droplets deposit...
FIG. 8. The velocity diagrams of the axial symmetrical section of the double disks under different AGPs: (a) $2.0 \times 10^5$ Pa, (b) $2.5 \times 10^5$ Pa, (c) $3 \times 10^5$ Pa, (d) $3.5 \times 10^5$ Pa, and (e) $4.0 \times 10^5$ Pa. Figures 8(a1)–8(e1) show the VFs of the whole simulation region, and Figs. 8(a2)–8(e2) reflect the simulation regions near the spray nozzle.
FIG. 9. The TFs of the axial symmetrical section of the double disks under different AGPs: (a) $2.0 \times 10^5$ Pa, (b) $2.5 \times 10^5$ Pa, (c) $3 \times 10^5$ Pa, (d) $3.5 \times 10^5$ Pa, and (e) $4.0 \times 10^5$ Pa.
FIG. 10. The TFs of the axis of the tube under different AGPs: (a) $2.0 \times 10^5$ Pa, (b) $2.5 \times 10^5$ Pa, (c) $3 \times 10^5$ Pa, (d) $3.5 \times 10^5$ Pa, and (e) $4.0 \times 10^5$ Pa.

D. Experimental verification

For a better comparison effect, the metal melt is sprayed directly on the stationary plane substrate, as shown in Fig. 11. Figure 12(a) shows the morphologies of the deposited billets at five different AGPs. When the AGP is lower ($2.0 \times 10^5$ Pa), the cross-flow of gas is strengthened by the interference of the two disks, which results in a larger lateral distance of droplet deposition. Moreover, the liquid content of the deposited blank is high because the cooling ability is weak under low AGP. Thus, the width of the billet is larger, which does not match the basement of the extruded wheel groove. However, the reverse flow near the basement is larger when the AGP is higher ($3.5$–$4.0 \times 10^5$ Pa). The droplets will be taken out of the basement, which makes the controllability worse. Also, the blockage of the diversion tube is prone to occur because of the strong cooling ability under high AGP, as shown in Fig. 12(b). Fortunately, the metal melt can not only flow out from the diversion tube smoothly but also obtain good controllability of droplet deposition between $2.5 \times 10^5$ and $3.0 \times 10^5$ Pa.

IV. CONCLUSION

The flow fields of RCCSD were simulated by FLUENT. The following findings were obtained through experimental verification.

1. The influence of AGP on PF. The PF near the axis of the diversion tube corresponds positively to the AGP. When the AGP is lower, the gas flow is more comfortably disturbed by the double disks, and the transverse gas flow is strengthened, which is not conducive to controlling the deposition of droplets. When the AGP is higher, a more significant positive pressure area is formed near the base, which is not conducive to the deposition of droplets. When the AGP is between $2.5 \times 10^5$ and $3.0 \times 10^5$ Pa, the outlet pressure of the diversion tube is about $2.5 \times 10^4$ Pa, and the pressure near the base is about $5 \times 10^4$ Pa. It is controllable for droplet deposition. The deposited blank shape is suitable to match the basement of the extrusion groove.

2. The influence of AGP on VF. The VF is asymmetrical under the power of the two disks. The velocity near the edges of the disks is significant, while that near the center is small. The turbulence intensity decreases with the increase in AGP. When the AGP is lower ($<3.0 \times 10^5$ Pa), there are two velocity stagnation points at about 13 and 20 mm, respectively. However, when the AGP is higher ($>3.0 \times 10^5$ Pa), there is only a velocity stagnation point at about 20 mm. The values of the stagnation points are all greater than 100 m/s in any case.

3. The influence of AGP on TF. The TF deviates to one side near the base along the direction of the linear velocity of the double-disk. The outlet temperature of the diversion tube is low when the AGP is high, leading to a quick blockage. The temperature of the axis of the diversion tube drops rapidly at about 13 mm after a short stay and then tends to be flat, indicating that the melt is atomized at this position. About 38% of the total heat is retained when the droplets deposit on the substrate, which provides the necessary conditions for hot extrusion.
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