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ABSTRACT
Parallel shearing flows significantly affect the structure of the magnetic reconnection layer and generate new shock structures such as intermediate shock (IS) and time-dependent IS. The strength of shock waves (such as slow shock) can be changed and result in the switch-off of magnetic reconnection under certain conditions. In this study, we perform numerical simulations of one-dimensional resistive magnetohydrodynamic equations by using the total variation diminishing algorithm to investigate the influence of parallel shear flow on the switch-off effect of magnetic reconnection on both asymmetric and symmetric magnetic reconnection layers. Numerical results show that there exists a critical shear velocity $V_{zc}$ that equals $V_A$ in symmetrical antiparallel magnetic reconnection, where $V_A$ denotes the inflow Alfvén velocity. For symmetric component magnetic reconnection, $V_{zc}$ drops with the increase in guide magnetic field strength, which also equals the component of inflow Alfvén velocity along the $z$-axis. In regard to asymmetric magnetic reconnection, the critical shear velocity, $V_{zc}$, that leads to the switch-off of magnetic reconnection, ranging between the $z$-axis components of inflow Alfvén velocity in the magnetosheath and in the magnetosphere. A new parameter associated with the Alfvén velocity on both sides is proposed; for both antiparallel reconnection and component reconnection, this new parameter equals the critical shear velocities.

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I. INTRODUCTION

There are many regions in space that are prone to magnetic reconnection. During the magnetic reconnection process, the energy of a magnetic field can be rapidly transformed into the kinetic energy of plasma. Energy release is quite important for large-scale magnetic field structures, in which magnetic reconnection is of great significance to space plasma dynamics.1–11

Magnetic reconnection was introduced into magnetospheric physics by Dungey in 1961. The reconnection of magnetic lines occurs in a plasma region with antiparallel magnetic-field components. Magnetic energy can be effectively transformed into kinetic energy via reconnection, thereby leading to the ejection of high-velocity plasma. Magnetohydrodynamic (MHD) discontinuity and the stratified structure of an expansion wave can be found in reconnection outflow regions. The stratified plasma is referred to as the reconnection layer. Several theoretical models of magnetic reconnection have been proposed,12–14 in which the reconnection layer is only a simple structure with one or two discontinuities. However, the stratified structures observed in day-side magnetopause boundary layer and night-side plasma sheet are quite complex15–18 and cannot be explained by the above-mentioned ideal models. Therefore, many literature studies examined the structure of the reconnection layer in magnetic reconnection outflow region via MHD theoretical analysis and numerical simulations.19–23 It has been proved that the intermediate shock (IS) develops from continuous wave (CW) under resistive effects.24,25 Shi and Lee employed a two-dimensional (2D) resistance MHD model for analyzing the structures of the reconnection layer under different symmetrical conditions and found that IS may appear in the reconnection layer.26 Scholer investigated the stable magnetic reconnection of day-side magnetopause and found the existence of IS.27 On the other side, in recent research on guide magnetic field, the magnetic field was no longer coplanar and its strength was nonconservative. Since the coplanar condition of IS is broken down in the structure, the Rankine-Hugoniot (RH) condition for stable shock was
no longer satisfied and time-dependent IS appeared. Similar to the rotatory shock, rotational discontinuity (RD) appears in ideal MHD models, TDIS can change the direction of the tangential magnetic field, while both its width and strength change with time. As time tends to infinity, TDIS degrades into RD. Both theoretical analysis and numerical simulations indicate that stable IS and TDIS play the same role as RD in the reconnection layer.

The above studies were focused on symmetric reconnection structure. In reality, however, the reconnection is mostly asymmetric with nonuniform density, temperature, and magnetic field strength in the inflow region. Asymmetric reconnection always occurs in the magnetopause. Asymmetric lobe reconnection may also occur in the magnetotail with unbalanced development, especially in the case of strong east and west magnetic-field components.

Another important factor that affects the structure of a reconnection layer is the existence of shear flows. For example, shear flows exist in high-latitude magnetopause and magnetotail of the Earth as well as on both sides of the magnetosphere. Asymmetric lobe reconnection may also occur in the magnetotail with unbalanced development, especially in the case of strong east and west magnetic-field components.

Most of the previous studies adopted low-precision and low-resolution numerical calculation algorithms. In fact, in regard to the numerical algorithm with low spatial precision and shock resolution because of considerably numerical viscosity, the wave system structure in the reconnection layer was smoothed, and therefore, small-scale variation of some physical quantities in the shock and expansion wave could not be distinguished. In this study, using the high-resolution Total Variation Diminishing (TVD) algorithm, the influence of parallel shearing flows on the switch-off effect of symmetric and asymmetric magnetic reconnection under different guide magnetic fields was systematically investigated. Some new fine structures and evaluation characteristics of the reconnection layer were captured accurately, which can enhance knowledge of wave system structures in the reconnection layer.

The main motivation of our study was to investigate the influence of parallel shearing flow on the switch-off effect of the magnetic reconnection. On one aspect, it is a common phenomenon that asymmetric reconnection occurs on the magnetopause. Asymmetric lobe reconnection may also occur in the magnetotail with unbalanced development, especially in the case of strong east and west magnetic-field components. On another aspect, shear flows exist in high-latitude magnetopause and magnetotail of the Earth as well as on both sides of the magnetosphere. In addition, shearing flow can lead to the switch-off effect of magnetic reconnection. Although previous literature has analyzed the critical shearing velocity that led to the annihilation of magnetic reconnection under incompressible conditions and pointed out that its value equaled the Alfvén velocity of the inflow region, it is necessary to study the annihilation of magnetic reconnection under compressible conditions.

II. 1D MHD MODEL

Reconnection is basically a 3D phenomenon. Although attempts have been made to study the 2D and the 3D configuration of the reconnection layer by using MHD simulations, the discontinuities and expansion waves obtained in these simulations have not been clearly identified and studied due to low spatial resolution and small simulation domain. A clear separation between discontinuities usually requires a long simulation time and thus a very long simulation domain along the out-flow direction. In order to identify clearly the discontinuities and expansion waves in the reconnection layer, we can simplify the 2D problem to 1D initial value problem by assuming that the physical quantities are functions of \( x \) and \( t \). What the simplified 1D magnetic reconnection focuses on is to figure out the detailed configuration of the reconnection layer after the onset of magnetic reconnection but not the change in the topology of magnetic fields. So, we just assume that the magnetic field line is reconnected at \( t = 0 \). The solution of the Riemann problem corresponds to a quasi-steady reconnection configuration in which the separatrix angle is small.

The magnetic field strength was represented by the strength of far magnetic field \( B_\infty \), and the velocity was represented by the Alfvén velocity of the far magnetic field \( V_{A\infty} = B_\infty / \sqrt{\mu_m \rho_\infty} \) for dimensionless processing. The characteristic length was set to \( \delta = a/2 \), where \( a \) is the width of the current sheet. Therefore, the following dimensionless parameters were used:

\[
\begin{align*}
\tau^* &= \frac{t V_{A\infty}}{\delta}, \quad x^* = \frac{x}{\delta}, \quad V_x^* = \frac{V_x}{V_{A\infty}}, \quad V_y^* = \frac{V_y}{V_{A\infty}}, \quad V_z^* = \frac{V_z}{V_{A\infty}}, \\
p^* &= \frac{p}{\rho_\infty V_{A\infty}^2}, \quad \rho^* = \frac{\rho}{\rho_\infty}, \quad B_x^* = \frac{B_x}{B_\infty}, \quad B_y^* = \frac{B_y}{B_\infty}, \quad B_z^* = \frac{B_z}{B_\infty}, \\
\mu^* &= \frac{\mu}{\mu_{m\infty}}, \quad \eta^* = \frac{\eta}{\eta_\infty}, \quad \mu_{m\infty} = \frac{\mu_{m\infty}}{\rho_\infty V_{A\infty}^2},
\end{align*}
\]

where \( \delta \) is the reference length that is the half width of the boundary layer, \( V \) is the velocity vector, \( B \) is the magnetic field vector, \( V_A \) is the Alfvén velocity, \( p \) is the plasma pressure, and \( \rho \) is the plasma density. The subscript \( n \) represents the dimensional quantities, and the superscript asterisk (*) denotes normalized variables. For better readability, the asterisks are skipped in the following equations. By taking into account viscosity, heat conduction, resistance, and Hall effect of the plasma, the 1D MHD equations can be written as...
\[ P = p + \frac{V^2}{2} \text{ and } \rho = \frac{P}{\mu + \frac{V^2}{2}}. \] The viscosity coefficient \( \mu \) can be calculated according to the Sutherland formula,

\[ \mu = (T)^{1.5} \left( \frac{1 + \frac{T_i}{T}}{1 + \frac{T}{T_i}} \right) = 110.4 \left( \frac{T}{T_{\infty}} \right)^{1.5}. \] (3)

The dimensionless parameters in Eq. (2) can be expressed as follows:

- Reynolds number: \( Re = \frac{\rho V \lambda_{mol}}{\mu} \)
- Prandtl number: \( Pr = \frac{\mu}{\rho C_p} \)
- Mach number: \( M_0 = \frac{V}{\sqrt{\frac{R T_0}{\rho}}} \)
- Magnetic Reynolds number: \( R_m = \frac{\mu_{m0} \sigma \infty V A_{\infty} \delta} \)
- Hall parameter: \( H = \omega \tau_c \).

### III. NUMERICAL SCHEME

Equation (2) can be rewritten in the vector format as

\[ \frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} = \mathbf{S}_r + \mathbf{S}_{mv} + \mathbf{S}_h. \] (4)

The calculation algorithm of the 1D nonlinear MHD equation can be written as

\[ \mathbf{Q}_{i+1}^{n+1} = \mathbf{Q}_i^n - \Delta t \frac{\delta \mathbf{F}_i}{\Delta x}. \] (5)

where

\[ \delta \mathbf{F}_i = \mathbf{F}_{i+\frac{1}{2}} - \mathbf{F}_{i-\frac{1}{2}}, \quad \mathbf{F}_{i\pm\frac{1}{2}} = \mathbf{F}(Q_{i-1}, Q_i, Q_{i+1}), \]

\[ \mathbf{F}_{i\pm\frac{1}{2}} = \mathbf{F}_{i\pm\frac{1}{2}}(Q_{i-1}, Q_i, Q_{i+1}, Q_{i+2}). \] (6)

According to the numerical flux of the Harten second-order Total Variation Diminishing (TVD) algorithm,\(^{[44]}\) the numerical flux can be written as

\[ F = \frac{1}{2} (F_{i+1} + F_i) + R_{\text{Roe}}(Q_{i-1}, Q_i) \times \left[ \frac{g'_{i+\frac{1}{2}} + g'_{i-\frac{1}{2}}}{2} Q_i \left( \lambda_{\text{Roe}}(Q_{i-1}, Q_i) + \mu \right) \right] I_{\text{Roe}}(Q_{i-1}, Q_i)(Q_i - Q_{i-1}), \]

\[ = \frac{1}{2} \left[ Q_i \left( \lambda_{\text{Roe}}(U_{i-1}, U_i) - \Delta t \left( \lambda_{\text{Roe}}(U_{i-1}, U_i) \right)^2 \right) \right] \times I_{\text{Roe}}(U_{i-1}, U_i)(U_i - U_{i-1}), \]

\[ \mathbf{g}'_{i+\frac{1}{2}} = \text{superbee}(g'_{i+1}, g'_{i}), \]

\[ \mathbf{g}'_{i} = \text{superbee}(g'_{i+1}, g'_{i}). \] (7)

\[ \mu = \frac{g'_{i+\frac{1}{2}} - g'_{i-\frac{1}{2}}}{I_{\text{Roe}}(U_{i-1}, U_i)(U_i - U_{i-1})}, \] (10)

\[ g'_{i+\frac{1}{2}} = \frac{1}{2} \left[ Q_i \left( \lambda_{\text{Roe}}(U_{i-1}, U_i) - \Delta t \left( \lambda_{\text{Roe}}(U_{i-1}, U_i) \right)^2 \right) \right] \times I_{\text{Roe}}(U_{i-1}, U_i)(U_i - U_{i-1}), \] (11)

\[ g'_{i} = \frac{1}{2} \left[ Q_i \left( \lambda_{\text{Roe}}(U_{i-1}, U_i) - \Delta t \left( \lambda_{\text{Roe}}(U_{i-1}, U_i) \right)^2 \right) \right] \times I_{\text{Roe}}(U_{i-1}, U_i)(U_i - U_{i-1}). \] (12)
\[ g^i = \frac{1}{2} \left[ \mathcal{Q}_i \left( \lambda_{\text{Roe}}(U_i, U_{i+1}) \right) - \Delta t \left( \lambda_{\text{Roe}}(U_i, U_{i+1}) \right)^2 \right] \times \mathcal{L}_{\text{Roe}}(U_i, U_{i+1})(U_{i+1} - U_i), \]

(13)

superbee \( (a, b) = \frac{\text{sgn}(a) + \text{sgn}(b)}{2} \cdot \max\left[ \min(2|a|, |b|), \min(|a|, 2|b|) \right] \),

(14)

where \( \mathbf{R}_{\text{Roe}}, \mathbf{L}_{\text{Roe}}, \) and \( \lambda^i_{\text{Roe}} \) denote the right and left eigenvectors and eigenvalues of 1D MHD after Roe averaging. The 1D ideal MHD equation is nonlinear. For maintaining the linearized calculation algorithm conservative and consistent with the original non-linear equation (also in the case of numerical difficulties, such as the Riemann discontinuity), the calculation of the wave structure was improved, and the Roe average was introduced for satisfying the so-called "U" property. Accordingly, Roe average values of the variables of both field and magnetic field can be expressed as

\[ \hat{\rho} = \frac{1}{2} \left( \sqrt{\rho R} + \sqrt{\rho L} \right)^2, \]

(16)

\[ \hat{V}_y = \frac{\sqrt{\rho R} V_{yR} + \sqrt{\rho L} V_{yL}}{\sqrt{\rho R} + \sqrt{\rho L}}, \]

(17)

\[ \hat{V}_z = \frac{\hat{\rho}}{\hat{\rho}} \hat{W} = \frac{\sqrt{\rho R} V_{zR} + \sqrt{\rho L} V_{zL}}{\sqrt{\rho R} + \sqrt{\rho L}}, \]

(18)

\[ \hat{B}_y = \frac{1}{4} \left( \sqrt{\rho R} + \sqrt{\rho L} \right) \left( \frac{B_{yR}}{\sqrt{\rho R}} + \frac{B_{yL}}{\sqrt{\rho L}} \right), \]

(19)

\[ \hat{B}_z = \frac{1}{4} \left( \sqrt{\rho R} + \sqrt{\rho L} \right) \left( \frac{B_{zR}}{\sqrt{\rho R}} + \frac{B_{zL}}{\sqrt{\rho L}} \right), \]

(20)

\[ \hat{h} = \frac{\sqrt{\rho R} h_{R} + \sqrt{\rho L} h_{L}}{\sqrt{\rho R} + \sqrt{\rho L}}. \]

(21)

The right end item of Eq. (2) was discretized with central differences.

**IV. NUMERICAL RESULTS**

This study adopted the second-order TVD scheme with Roe averaging for solving the 1D MHD equations and performed numerical simulations on two different types of reconnection layer structures, namely, antiparallel reconnection and component reconnection when the initial current sheets were symmetric or asymmetric. Figure 1 illustrates the coordinate system used for representing the reconnection layer.

All physical quantities are functions of time \( t \) and position \( x \) along the current sheet normal direction which is distinct with the two-dimensional solution that the normal to the current sheet is in the \( x \) direction, and the current sheet is located along \( x = 0 \). The magnetic field component along the \( z \) direction can be written as

\[ B_{2\text{Re}}(x) = \frac{1}{2} \left( B_{2\text{in}} + B_{2\text{out}} + \frac{1}{2} \left( B_{2\text{in}} - B_{2\text{out}} \right) \tanh(x) \right), \]

(22)

where the subscript "0" denotes physical quantities at \( t = 0 \) and subscripts "m" and "s" denote magnetosphere and magnetosheath, respectively. In order to make the current sheet satisfy the condition \( \nabla \cdot \mathbf{B} = 0 \), \( B_{x0} \) was set to a constant \( B_{x0} = B_{x\infty} \). The total magnetic field can be expressed as

\[ B_0(x) = B_{x\infty} \delta_z + B_{y\infty} \delta_y + B_{z\infty} \tanh(x) \delta_z. \]

(23)

In the above formulas, \( \theta \) is the angle between the far magnetic field and the \( x \)-axis; \( \phi_0 \) is the angle between the far tangential magnetic field and the \( z \)-axis. If \( B_\infty = \sqrt{B_{x\infty}^2 + B_{y\infty}^2 + B_{z\infty}^2} \) denotes the strength of the far magnetic field, its components are \( B_{x\infty} = B_{x\infty} \cos \theta, B_{y\infty} = B_{y\infty} \sin \theta \sin \phi_0, \) and \( B_{z\infty} = B_{z\infty} \sin \theta \cos \phi_0 \).

At the initial time of \( t = 0 \), the total pressures through the current sheet reached equilibrium, i.e.,

\[ p_0(x) + \frac{B_{x0}^2}{2\mu_m} = \text{Const}. \]

(24)

If the plasma \( \beta \) is given, the pressure \( p_\infty \) of plasma in the far magnetic field can be determined, and therefore, the initial pressure distribution in the whole flow field at \( t = 0 \), \( p_0(x) \), can be derived.

If the initial current sheet was symmetric, it can be assumed that the system at \( t = 0 \) satisfied the adiabatic process of ideal plasma, i.e., satisfied entropy conservation condition. Accordingly, \( p_0(x)p_\infty(x)^{-\gamma} = \text{Const}, \) and the density distribution of the initial current sheet can be determined.

FIG. 1. Coordinate system used for the reconnection layer in which "L" and "R" denote the left side and the right side, respectively. \( B_L, \mathbf{V}_L, B_R, \) and \( \mathbf{V}_R \) indicate the magnetic field and flow on the left and right sides on the outflow, and the dotted lines show the position of the outgoing wave discontinuity.
The above physical quantities were dimensionless. In order to determine the structure of the reconnection layer under symmetric density and magnetic field, $\theta$, $\phi_0$, $\beta$, $V_{z\infty}$ (the velocity of parallel shear flow in the far magnetic field), as well as some dimensionless quantities $Re$, $H$, and $R_m$ should be known. This study did not take viscosity and the Hall effect into consideration and set $R_m = 1000$. 2000 mesh points in total were used in the calculation which covered the domain from $x = -1000$ to $x = 1000$.

A. Symmetric antiparallel reconnection

Figure 2 displays the distribution patterns of $V_z$, $\rho$, $T$, $p$, $B_z$, and $J_y$ under different parallel shearing flows at $t = 1500$. Results corresponding to $V_{z\infty} = 0$, 0.2, and 1 were plotted by a dotted line, a dashed line, and a solid line, respectively. For the convenience of comparison, the parameter distribution pattern of $V_z$ at $V_{z\infty} = 1.5$ was plotted by a dotted-dashed line (the same graphic representation is used in Figs. 3, 5, and 6). At the initial time, the current sheet was located at $x = 0$, and the initial parameters were set to $\theta = 70^\circ$, $\beta = 0.2$, and $\phi_0 = 0^\circ$, i.e., for the guide magnetic field, $B_y = 0$.

It can be observed from Fig. 2 that parallel shearing flow destroyed the symmetric structure of the reconnection layer. Moreover, as the initial velocity of the parallel shearing flow increased, the left SS weakened, while the right SS strengthened and evolved into IS. The density, pressure, and temperature of IS all increased; $B_z$ decreased; and the direction of the magnetic field was changed by $180^\circ$.

From the distribution pattern of $V_z$ in Fig. 2, it can be observed that the outflow accelerated region was restricted by a SS and an IS at a small initial parallel shear velocity. As the initial parallel shear velocity $V_{z\infty}$ increased, SS weakened and IS strengthened. As $V_{z\infty}$ reached a critical value, the left SS and the outflow acceleration region disappeared, leading to the switch-off of magnetic reconnection. Therefore, the critical point corresponding to the disappearance of SS can be regarded as the critical point of the switch-off of magnetic reconnection. In this study, under the selected initial condition of symmetrical antiparallel magnetic reconnection, the critical value of initial shear velocity equaled 1, i.e., $V_{zc} = 1$, which also was the Alfvén velocity of the inflow region. This conclusion is consistent with the results reported by Mitchell and La Belle-Hamer.\[42,43\]

It can also be observed from the distribution pattern of $V_z$ that a slow expansion (SE) wave appeared on the left when $V_{z\infty} > V_{zc}$. Therefore, the postwave region no longer accelerated but decelerated.

B. Symmetric component magnetic reconnection

Figure 3 displays the distribution patterns of $V_z$, $\rho$, $T$, $p$, $B_z$, and $J_y$ under different parallel shearing flows at $t = 1500$. In this case, plotted results correspond to $V_{z\infty} = 0$, 0.2, and 0.84. The initial
FIG. 3. Structure of the reconnection layer with symmetrical components in the case of parallel shear flow. (a) The velocity component $V_z$ as a function of the transverse position $x$. (b) The plasma density $\rho$ as a function of the transverse position $x$. (c) The plasma pressure $p$ as a function of the transverse position $x$. (d) The absolute temperature $T$ as a function of the transverse position $x$. (e) The magnetic field component $B_y$ as a function of the transverse position $x$. (f) The magnetic field component $B_z$ as a function of the transverse position $x$. (g) The current density component $J_y$ as a function of the transverse position $x$. (h) The current density component $J_z$ as a function of the transverse position $x$.

parameters were set to $\theta = 70^\circ$, $\beta = 0.2$, and $\phi_0 = 30^\circ$. At that time point, for the guide magnetic field, $B_{y0} = 0.47$.

As shown in Fig. 3, a pair of time-dependent intermediate shocks (TDISs) or time-dependent rotational discontinuities (TDRDs) appeared in the reconnection of components, which fits with the results published by Wu and Lin.\textsuperscript{19,20} Plasma exhibited decreasing density, pressure, temperature, and tangential magnetic field strength when passing through TDIS. This evolution proceeded with the rotation of the tangential magnetic field. TDIS evolved into TDRD. When the plasma flowed through TDIS, density, pressure, temperature, and tangential magnetic field strength remained unchanged, and only the tangential magnetic field was rotated.

A pair of slow shock (SS) waves followed the TDIS. Due to the effect of the temporal properties of TDIS, the strength of SS also changed with time.\textsuperscript{13} This process can thus be referred to as “quasi-slow-shock.”\textsuperscript{23}

It can also be observed from Fig. 3 that parallel shearing flow also had initial critical velocity $V_{zc}$, which is similar to the condition of antiparallel reconnection. When $V_{\infty} = V_{zc}$, SS on the left side, TDIS, and the outflow accelerating region disappeared, thereby resulting in the switch-off of magnetic reconnection. The difference lies in the drop of the critical velocity of parallel shearing flow because of the effect of the guide magnetic field. When $\phi = 30^\circ$, $V_{zc} = 0.84$.

Further analysis showed that the Alfvén velocity of the inflow region equaled 1 and was therefore different from $V_{zc}$. In fact, it can be observed that $V_{zc} = V_{Adm} = \frac{B_{zm0}}{\sqrt{\mu_0 \rho_{m0}}}$. For validating the above conclusion, the variation of $V_{zc}$ with $\phi_0$ when $\theta = 70^\circ$ was also plotted, as shown in Fig. 4. At a large $\phi_0$, magnetic
reconnection can be switched off by weak parallel shear flow; Fig. 4 also displays the variation of $V_{Azm}$ with $\phi_0$. Apparently, when $\phi_0 \geq 30^\circ$, $V_{zc} = V_{Azm}$; when $\phi_0 < 30^\circ$, $V_{Azm}$ was slightly smaller than $V_{zc}$; and when $\phi_0 \leq 10^\circ$, $V_{zc} = V_{Am} = B_{zm} \sqrt{\mu m / \rho m \infty}$. Previous literature also analyzed the magnetic field component perpendicular to the current sheet and the guide magnetic field and concluded that $V_{zc}$ equaled the Alfvén velocity of the inflow region.\cite{42,43} In fact, it can also be observed from Fig. 4 that the above conclusion was a particular case, and $V_{zc}$ should be the component of the Alfvén velocity of the inflow region along the $z$-axis direction.

C. Asymmetric antiparallel magnetic reconnection

Figure 5 displays the distribution patterns of $V_z$, $\rho$, $T$, $p$, $B_z$, and $J_y$ in asymmetric antiparallel magnetic reconnection under different parallel shearing flows. In this case, plotted results correspond to $V_{zc0} = 0$, 0.2, and 0.87. The initial parameters were set to $\theta = 70^\circ$, $\beta = 0.2$, and $\phi_0 = 0^\circ$. At that time point, for the guide magnetic field, $B_{y0} = 0$.

As shown in Fig. 5, at a small $V_{zc0}$, fast expansion (FE) waves, intermediate shock (IS), slow expansion (SE) waves, and contact discontinuity (CD) appeared successively at the left side of the magnetosheath in the reconnection layer, while SE and SS appeared successively at the right side of the magnetosphere. As $V_{zc0}$ increased, IS on one side of the magnetosheath weakened, while SS on the other side became stronger. As $V_{zc0}$ increased to $V^*$ (the critical velocity corresponding to shock transformation), IS at one side of the magnetosheath was converted to SS, and simultaneously, two annihilated SSs appeared on both sides of the reconnection layer. This agrees well with the results published in Refs. 13 and 34. Lin et al. also derived the analytical expression of $V^*$ in Ref. 13: $V^* = (|V_{Azm}| - |V_{Azs}|)/2$.\cite{13,34}

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**FIG. 4**. Variation of critical shear velocity $V_{zc}$ with the angle between the far tangential magnetic field and the $z$-axis $\phi_0$.

**FIG. 5**. Structure of the asymmetrical antiparallel magnetic reconnection layer with parallel shear flow. (a) The velocity component $V_z$ as a function of the transverse position $x$. (b) The plasma density $\rho$ as a function of the transverse position $x$. (c) The plasma pressure $p$ as a function of the transverse position $x$. (d) The absolute temperature $T$ as a function of the transverse position $x$. (e) The magnetic field component $B_z$ as a function of the transverse position $x$. (f) The current density component $J_y$ as a function of the transverse position $x$.\cite{13,34}
As \( V_{z,\infty} \) increased to a critical velocity \( V_{zc} \), SS at one side of the magnetosheath disappeared at which time the magnetic reconnection was switched off. Further analyses reveal that the critical velocity \( V_{zc} \) ranged between \( V_{Azm} \) and \( V_{Azs} \). Accordingly, the mixed magnetic field strength can be introduced as
\[
\bar{B}_z = \frac{2B_{zm}B_{zs}}{B_{zm} + B_{zs}}. \tag{27}
\]
Under these conditions, the generated Alfvén velocity at one side of the magnetosheath can be defined as
\[
\bar{V}_{Azm} = \frac{\bar{B}_z}{\sqrt{\mu_0 \rho_m}} = \frac{2B_{zm}B_{zs}}{(B_{zm} + B_{zs})\sqrt{\mu_0 \rho_m}}. \tag{28}
\]
Comparisons indicate that \( V_{zc} = \bar{V}_{Azm} \). The structure of the reconnection layer was plotted by the solid line in Fig. 5.

**D. Asymmetric component magnetic reconnection**

Figure 6 displays the distribution patterns of \( V_z, \rho, T, p, B_z, \) and \( J_z \) in asymmetric component magnetic reconnection with parallel shearing flows. In this case, plotted results correspond to \( V_{z,\infty} = 0, 0.2, \) and \( 0.76 \). At \( t = 0 \), the current sheet was located at \( x = 0 \), while the initial parameters were set to \( \theta = 70^\circ, \beta = 0.2, \) and \( \phi_0 = 30^\circ \). For the guide magnetic field, \( B_{y0} = 0.47 \).

It can be observed from Fig. 6 that, at a small \( V_{z,\infty} \), FE, TDIS, SS, and CD appeared successively at the left side of the magnetosheath in the reconnection layer, and simultaneously, SE, SS, and TDIS appeared successively at the right side of the magnetosphere. With the increase in \( V_{z,\infty} \), TDIS and SS at one side of the magnetosheath weakened, while TDIS and SS at the other side strengthened. As \( V_{z,\infty} \) further increased to a critical value \( V_{zc} \), TDIS and SS at one side...
of the magnetosheath disappeared, and magnetic reconnection was switched off.

Figure 7 displays the variations of $V_{Zc}$ with $\phi_0$ when $B_{Zc} = -0.9B_{zm}$ and $B_{Zc} = -0.5B_{zm}$, while $V_{Azm} = B_{Zc}/\mu_0\mu_mBm$ and $V_{Azm} = B_{Zc}/\mu_0\mu_mBm$. Apparently, $V_{Zc}$ ranged between $V_{Azm}$ and $V_{Azs}$, and it held $V_{Zc} = V_{Azm}$.

V. RESULTS AND DISCUSSION

Magnetic field reconnection serves as an important energy release and transmission process in space and laboratory plasma which have always been of importance in plasma physics. In recent years, due to developments in satellite observation techniques, the effect of shearing flow on the structure of the reconnection layer has become an attractive topic in magnetic reconnection. Research results demonstrate that parallel shearing flow has a significant impact on the wave system structure of magnetic reconnection. On the one hand, some new SSs such as IS and TDIS can be generated. On the other hand, the strength of shocks such as SS in the magnetic reconnection can be changed, leading to the switch-off of magnetic reconnection under certain conditions.

This study used the TVD algorithm with Roe averaging for solving the resistive magnetohydrodynamic (RMHD) model and analyzed the structures of the symmetric and asymmetric magnetic reconnection layers with and without a guide magnetic field. The main conclusions supported by this investigation are described below.

(1) In the symmetric magnetic reconnection structure without a guide magnetic field, SS at the right side was replaced by IS because of the existence of parallel shear flows. SS at the left side weakened with the increase in shear velocity. As the shear velocity increased to the Alfvén velocity of the inflow region, magnetic reconnection was switched off.

(2) In the symmetric magnetic reconnection layer with a guide magnetic field, the outflow region was restricted by a pair of TDISs in the presence of parallel shearing flow, followed closely by a pair of SS waves. TDIS and SS at the left side weakened with the increase in shearing velocity. The switch-off of magnetic reconnection can be induced as the shearing velocity reaches the critical value. The critical shearing velocity equaled the component along the $z$-axis of the Alfvén velocity of the inflow region.

(3) In the asymmetric magnetic reconnection structure without a guide magnetic field, the inflow region was restricted by IS and SS. This behavior is similar to the one that occurs in the symmetric magnetic reconnection structure without a guide magnetic field. The difference between the two cases consisted in the fact that IS and SS were located at opposite positions. Therefore, IS at the side of magnetosheath weakened with increasing shearing velocity. As the shearing velocity increased to the critical velocity corresponding to shock transformation, $V^* = (|V_{Azm}| - |V_{Azs}|)/2$, IS was converted into SS. As the shearing velocity further increased, SS weakened steadily, and magnetic reconnection was switched off when the critical shearing velocity was reached. The critical shear velocity equaled the component of the Alfvén velocity on the side of magnetosheath along the $z$-axis component under mixed magnetic field strength, i.e., $V_{Zc} = V_{Azm}$, where $V_{Azm} = B_{m}/\sqrt{\mu_0\mu_mBm}$, $V_{Azs} = B_{s}/\sqrt{\mu_0\mu_mBm}$. Apparently, $V_{Zc}$ ranged between $V_{Azm}$ and $V_{Azs}$, and it held $V_{Zc} = V_{Azm}$.

(4) In the asymmetric magnetic reconnection structure with a guide magnetic field, the outflow region was restricted by a pair of TDISs, followed closely by a pair of SSs. This behavior was similar to that occurring in the symmetric magnetic reconnection structure with a guide magnetic field. As the shear velocity reached the critical value $V_{Zc} = V_{Azm}$, magnetic reconnection was switched off.

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