Formation of Alfvénic resonance layers in magnetic reconnection

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Abstract: In the framework of two-dimensional incompressible MHD, we investigate the formation of Alfvénic resonance layers with different super-Alfvénic shear flows. It is found that Alfvénic resonance layers are formed in the inflow region. The Alfvénic layers are located where the flow velocity equals to the local Alfvén speed and slowly drift away from the current sheet region as magnetic island develops. The presence of Alfvénic resonance layers can sufficiently suppress the magnetic reconnection. The suppressing effect depends largely on the intensity of the current density in Alfvénic resonance layers and the distance between two layers. As the velocity of the shear flow increases or the thickness of the shear flow reduces, the pair of Alfvénic layers tend to approach each other. The peak reconnection rate depends nonmonotonically on both the thickness a_v and the velocity v_0 of the shear flow. The maximum of the peak reconnection rate occurs at $v_0 = 1.2$ for the fixed thickness $a_v = 0.8$ and $a_v = 1.3$ for the fixed velocity $v_0 = 1.6$. There are thresholds for both the thickness and the velocity of the shear flow. Above the velocity threshold $v_0 \sim 1.5$ or below the thickness threshold $a_v \sim 0.85$, the peak reconnection rate is less than that of the case without an initially imposed shear flow and two magnetic islands are usually generated due to formation of Alfvénic resonance layers near the central current sheet.

Keywords: Magnetic reconnection, shear flows, Alfvénic resonances, incompressible MHD

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1. Introduction

Magnetic reconnection is an important process in space and laboratory plasmas, which provides a key mechanism for the energy conversion from the solar wind to the magnetosphere [*Dungey,* 1961]. It's widely regarded as magnetic reconnection can explain many observed phenomena in space, such as solar flare [*Giovanelli,* 1946] and magnetospheric substorm [*Angelopoulos et al.*, 2008].

Strong shear flow and magnetic shear generally coexist in the space environment, e.g., in the solar atmosphere and at the dayside magnetopause. The Kelvin-Helmholtz (KH) instability can be stimulated in the presence of a shear flow; the resistive tearing instability or magnetic reconnection occurs when the magnetic field is reversed with a small spatial scale. The shear flow in a magnetized plasma could have a significant impact on magnetic reconnection. Many researchers have investigated the effects of the shear flow on the resistive tearing mode [*Ofman et al.*, 1991,1993*; Chen and Morrison,* 1990*a, b; Li and Ma,* 2010, *Zhang et al.*, 2011, *Wu and Ma,* 2014] and the Kelvin-Helmholtz instability [*Miura,* 1982*; Chen et al,* 1997*; Shen and liu,* 1999].

Super-Alfvénic shear flow may lead to the development of the KH instability, the growth rate could highly be enhanced [*La Belle-Hamer et al,1988*]. Liu and Hu [1988] developed a new reconnection model so called a vortex-induced reconnection. If there is a strong velocity shear in the current sheet, the excited KH instability could produce large scale flow vortices. Consequently, the magnetic reconnection takes place due to the magnetic field line twist associated with flow vortices. The KH instability, in general, leads to a wavy current sheet and an "S" shape of magnetic islands. A fast shock can be formed due to the interaction between the strong shear flow and the magnetic island [*Shen et al, 2000*]. Knoll et al. [2002] found that the peak reconnection rate with a super-Alfvénic shear flow is not a function of the resistivity instead of a function of the initial shear flow. For a particular resistivity, the peak reconnection rate increases with increase of the super-Alfvénic shear flow. But, Alfvénic resonances can occur in the place where the flow velocity matches the local Alfvénic speed [*Hurricane et al,* 1995; *Wang et al,* 1998]. The generation of Alfvénic layers could strongly suppress the development of magnetic reconnection.

However, in the previous studies about the role of super-Alfvénic shear flows on magnetic reconnection the ratio $R = a_B / a_V$ is assumed to be one, where a_B and a_V are the thickness of the current sheet and the shear flow, respectively. Wang et al. [1998] analytically and numerically investigated the Alfvénic resonance effects on magnetic reconnection with the plasma rotation boundary. Alfvénic resonance layer formation with super-Alfvénic shear flows are also investigated based on the compressible MHD simulation model, but it is not systematically analyzed [Li and Ma, 2012]. In the present paper, we will systematically investigate different super-Alfvénic shear velocities and shear thicknesses. It's found that Alfvénic resonance layers formed in the inflow region can largely affect dynamic processes of magnetic reconnection. The paper is organized as follows: In section 2, we present the equations and numerical model. Section 3 shows the results of the simulation. The summary and discussion are given in section 4.

2. Equations and Numerical Model

The incompressible 2-dimensional MHD model is employed to investigate the instability with different super-Alfvénic shear flows. In our simulations, the Cartesian coordinate system is used, in which all quantities remain invariant in the z direction, that is $\partial / \partial z = 0$. The reduced MHD equations are as follows:

$$\frac{\partial \psi}{\partial t} = -\mathbf{v} \cdot \nabla \psi + \frac{1}{S} \nabla^2 \left(\psi - \psi_0 \right) \tag{1}$$

$$\frac{\partial \omega}{\partial t} = -\mathbf{v} \cdot \nabla \omega + \mathbf{B} \cdot \nabla J_z + \frac{1}{S_\upsilon} \nabla^2 \left(\omega - \omega_0 \right) \tag{2}$$

$$\omega = \nabla^2 \phi \tag{3}$$

$$J_z = \nabla^2 \psi \tag{4}$$

where $\mathbf{v} = \hat{z} \times \nabla \phi$, $\mathbf{B} = \hat{z} \times \nabla \psi$ with the assumptions $B_z = 0$ and $v_z = 0$. ω, J_z are the flow vorticity and the current in the z direction, respectively. $S = \tau_R / \tau_A$ is the Lundquist number and $S_\upsilon = \tau_\upsilon / \tau_A$ is the Reynolds number, where $\tau_A = a / v_A$ is the Alfvénic time, $v_A = B_0/(4\pi\rho)^{1/2}$ is the Alfvénic velocity, $\tau_R = 4\pi a^2/\eta c^2$ is the resistive diffusion time, $\tau_\upsilon = \rho a^2/\upsilon$ is the viscous diffusion time, a is the normalization unit of the length, c is the speed of light in the free space, η is the resistivity and υ is the viscosity. All variables have been normalized as follows: $\mathbf{x}/a \to \mathbf{x}$, $\mathbf{B}/B_0 \to \mathbf{B}$, $t/\tau_A \to t$, $\mathbf{v}/v_A \to \mathbf{v}$, $\psi/aB_0 \to \psi$, $\phi/av_A \to \phi$. In the incompressible plasma system, the density ρ is assumed to be uniform and always set to be 1. It should be emphasized that S and S_υ are constant.

Equations above are solved with fourth-order Runge-Kutta method in time and second-order finite difference method in space. The system size is $L_x = [-2, 2]$ and $L_y = [-4, 4]$ with 502×1001 uniform grid points in the x and y direction. Periodic boundary conditions are imposed at $x = \pm L_x$, while free boundary conditions are applied on $y = \pm L_y$. The initial magnetic field and plasma flow profiles are chosen to be the following forms:

$$\mathbf{B}(y) = B_0 \tanh(y/a_B)\hat{x} \tag{5}$$

$$\mathbf{v}(y) = -v_0 \tanh(y/a_v)\hat{x} \tag{6}$$

where a_v and a_B are the half thickness of the current sheet and the shear flow, B_0 and v_0 are the asymptotic values of the magnetic field and the shear flow velocity, respectively. We set $S = 1000$, $S_\upsilon = 10000$, $a_B = 0.2$, and $B_0 = 1.0$ to be fixed throughout this paper whereas a_v and v_0 are varied with $a_v \geq 0.6$ and $v_0 \geq 1$.

In our simulation, the magnetic reconnection rate E_r can be diagnosed by using the following method:

$$E_r = \eta[J(px) - J(po)] \tag{7}$$

Where px and po are the location of X and O points, respectively.

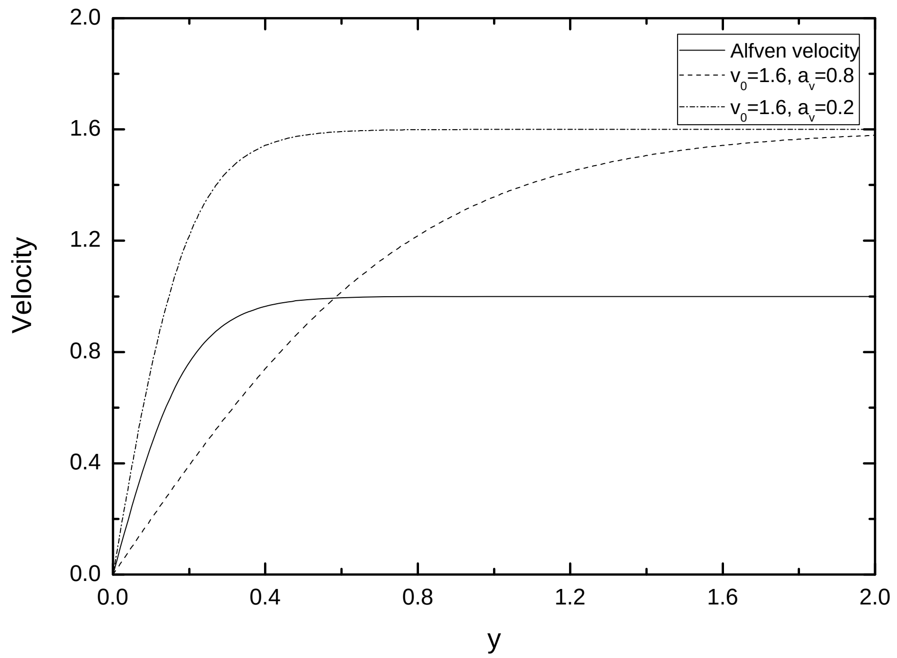

Figure 1. The profiles of the Alfvénic velocity (solid line) calculated from the local magnetic field and the shear flows for $a_v = a_B = 0.2$ (dash-dotted line) and $a_v = 4a_B = 0.8$ (dashed line).

3. Simulation results

The formation of Alfvénic resonances can occur in such configuration where the flow velocity matches the local Alfvénic speed, which can indicate from the follow equation:

$$\frac{d}{dy}\left[\mu_0\rho\left(\omega^2 - k_x^2 v_A^2\right)\frac{d\tilde{\xi}_y}{dy}\right] - k_x^2\mu_0\rho\left(\omega^2 - k_x^2 v_A^2\right)\tilde{\xi}_y = 0 \qquad (8)$$

The equation (8) is derived in the incompressible MHD model [Bellan, 1994].

The condition of Alfvénic resonances is satisfied when the thickness of super-Alfvénic shear flow is wider than that of the current sheet (the dashed line as shown in Figure 1). Most of previous works assume that a_v is equal to a_B, the condition can't be met (the dash-dotted line in Figure 1). Thus, the Alfvénic resonance layers in the presence of super-Alfvénic shear flow are seldom reported during magnetic reconnection. Also, we can easily find that the resonance condition, where the velocity initially imposed shear flow matches the local Alfvénic speed, can be well satisfied for the $v_0 > 1.0$ and $a_v > a_B = 0.2$ cases. The resonance position moves away from the current sheet as the initial shear flow thickness a_v increases for a given velocity v_0.

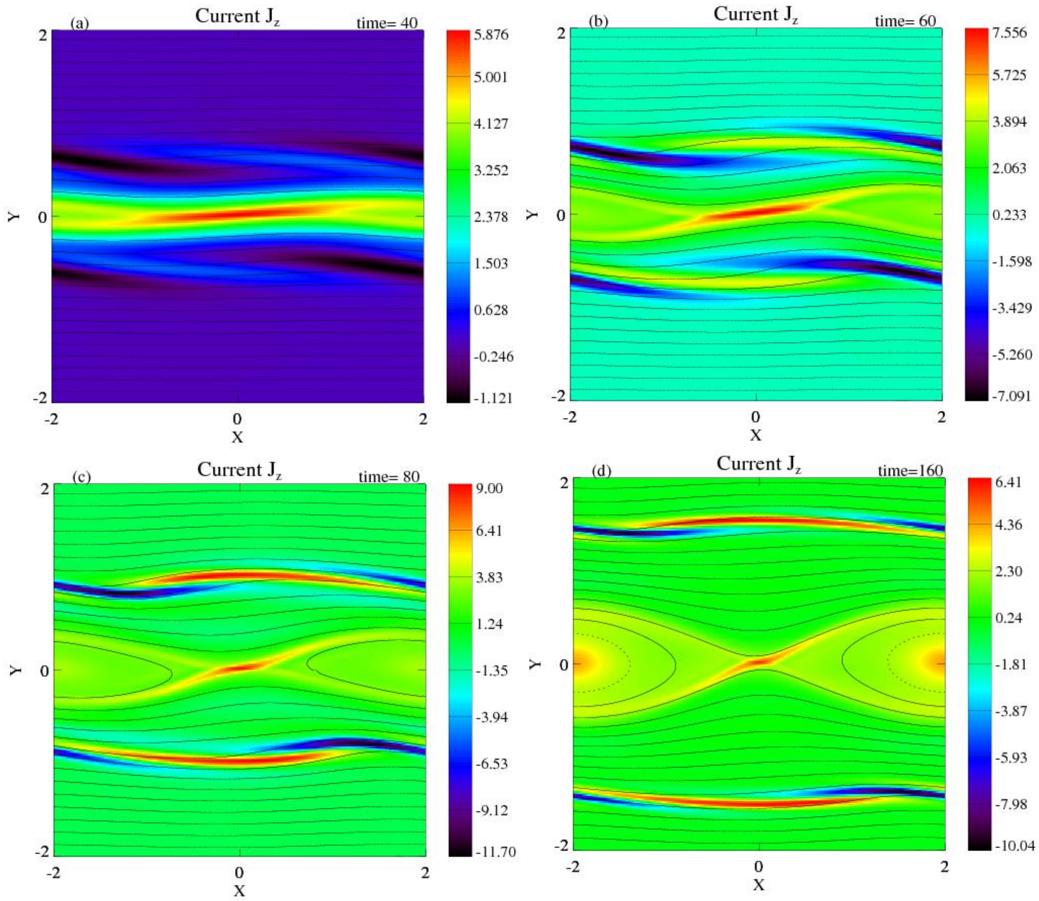

Figure 2. Contour plots of the current density distributions with magnetic field lines for $a_v = 4a_B = 0.8$ and $v_0 = 1.6$ at four different developed stages of magnetic reconnection.

A. Effects of asymptotic flow velocities for $a_v = 4a_B = 0.8$

In this section, we consider the cases with fixing the thickness of the shear flow $a_v = 4a_B = 0.8$ and varying its initial asymptotic flow velocity in the range [1.0, 2.0]. We mainly focus on the influence of initial asymptotic flow velocity on the magnetic reconnection evolution and the formation of resonance layers.

Figure 2 shows the distributions of the current density at different stage for $a_v = 4a_B$ and $v_0 = 1.6$. It's worth noting that only the half simulation domain of Y direction is plotted in Figure 2a-d. The four distinct phases are the "early rapidly changing phase", the "most rapidly changing phase", the "phase with maximum reconnection rate", and the "nearly saturated phase", respectively. In Figure 2a-b, we observe that the current sheet become wavy due to the KH disturbance, which is similar to those of the incompressible and compressible cases [*Liu and Hu*, 1988; *Pu et al*, 1990]. It's interesting to note that a pair of layers appears in Figure 2b and gradually becomes obvious, the initial locations of the Alfvénic resonance layers are about $y = \pm 0.6$ where the initial shear velocity equals to Alfvénic speed which can obviously get from Figure 1. Meanwhile, the magnetic islands have the shape of "S". As the island develops, the two resonance layers move away from each other slowly and finally become nearly stationary when the reconnection enters the saturated phase, as shown in figure 2c and figure 2d, then it exhibits a conventional reconnection configuration. The current density in the Alfvénic resonance layers increases quickly when the magnetic reconnection enters the "most rapidly changing phase", then slowly decreases, and finally tends to a steady state in the "nearly saturated phase".

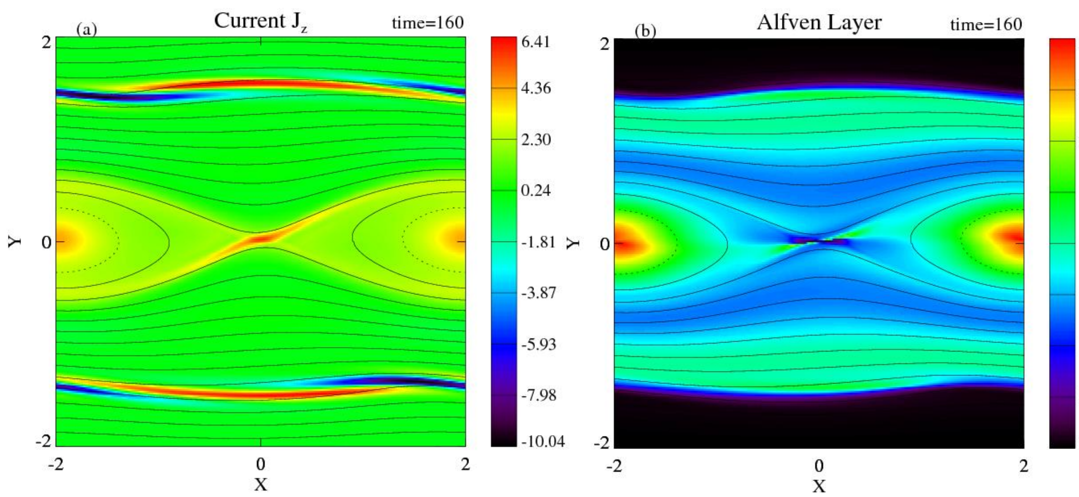

Figure 3. Contour plots of (a) the current density distribution (b) the ratio of the local Alfvénic speed and the flow velocity for $v_0 = 1.6$, $a_v = 4a_B$ at t=160.

The pair of the layers is Alfvénic resonances indeed, which is demonstrated in Figure 3. Figure 3b shows the distribution for the ratio of the local Alfvénic speed and the flow velocity. The locations of the resonance layers are approximately at the position where the ratio is equal to 1. There are no shocks formed outside the reconnection region, which is consistent with the results in a high beta plasma, it is unfavorable to the formation of the fast shocks [*Shen et al.,2000*]. The incompressible approximation means that the plasma beta is large without a strong guide field [*Biskamp, 2000*]. The reasons why there are no shocks are that the plasma flow generated by the magnetic reconnection only weakly changes the initially imposed shear flow because the Alfvénic resonance layers not only absorb the flow and magnetic energies generated by magnetic reconnection, but also prevent the strong shear flow from interacting with the magnetic islands.

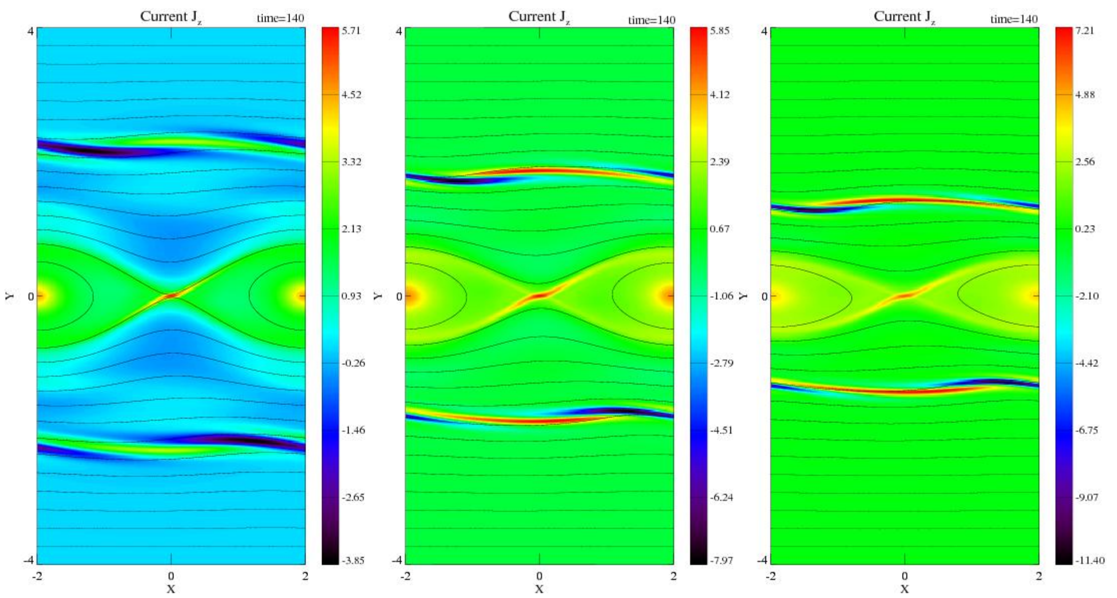

Figure 4. From left to right, the locations of Alfvénic Layers at the nearly saturated stage for the fixed $a_v = 4a_B$ cases with different shear velocities of $v_0 = 1.2$, $v_0 = 1.4$, and $v_0 = 1.6$, respectively.

Figure 4 presents the locations of the Alfvénic resonance layers of three cases at the same time t=140 with fixed $a_v = 4a_B = 0.8$ and different velocities $v_0 = 1.2$, $v_0 = 1.4$ and $v_0 = 1.6$, respectively. With the increase of the initial asymptotic flow velocity v_0, it is clearly seen that the current intensity in the Alfvénic resonance layers increases and the two resonance layers tend to be closer to each other. As the asymptotic shear flow velocity increases, the initial location of the resonance layers become closer to the current sheet as shown in Figure 1. The larger shear flow in the narrower range has more free energy from initial shear flow to drive a larger intensification of the current density in the Alfvénic resonance layers. The two closer and stronger resonance layers that can be treated as the barriers prevent the growth of the magnetic island. Therefore, the magnetic reconnection will be reduced as v_0 increases for a given shear flow thickness as shown in Figure 5. The dashed line represents the maximum reconnection rate for that case without the shear flow.

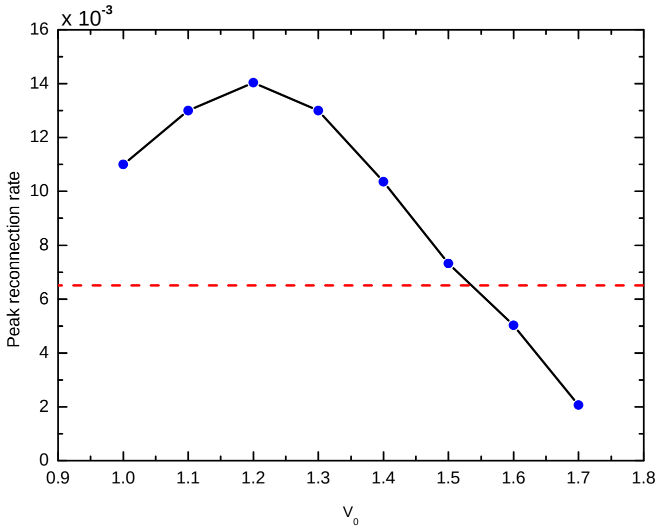

Figure 5. Peak reconnection rate related to different flow velocities for $a_v = 0.8$. The dashed line indicates the peak reconnection rate for case without the shear flow.

Clearly, in Figure 5, there is a turning point at which the peak reconnection rate begins to decrease with the increase of the shear velocity. As we know, KH instability and properties of Alfvénic resonance layers could affect magnetic reconnection. When the super-Alfvénic shear flow is less than $v_0 \sim 1.2$, the pair of Alfvénic layers is weaker and located far away from each other, so the KH instability controls the reconnection dynamics and enhances the growth of magnetic reconnection. Knoll and Chacon have already shown the boosting effect with the initial imposed super-Alfvénic shear flow as v_0 increases [Knoll and Chacon 2002]. As the velocity of the shear flow increases, the two resonance layers are located to close each other, magnetic reconnection is largely suppressed due to formation of the Alfvénic resonance layer. Therefore, the peak reconnection rate is reduced. Especially for the case $v_0 > 1.6$, the reconnection rate drops below that without super-Alfvénic shear flow, i.e., magnetic reconnection is suppressed by the super-Alfvénic shear flow, which is never reported before.

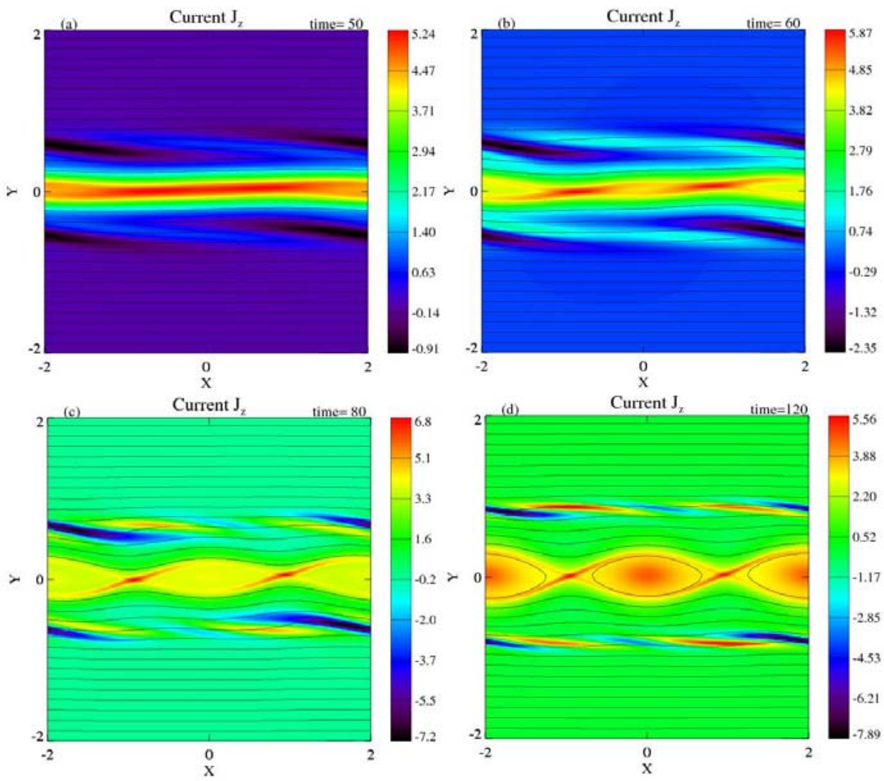

Figure 6. The evolution of the current density associated with magnetic field for $v_0 = 1.7$ and $a_v = 4a_B$.

To further investigate the detailed mechanism of suppressing effects of super-Alfvénic shear flow on magnetic reconnection, the time snapshots of the current density with magnetic field lines for $v_0 = 1.7$ and $a_v = 4a_B$ are shown in Figure 6. It is found that two magnetic islands emerge from the wavy current sheet. From the relationship between the Alfvénic resonance layer and the asymptotic flow velocity that has already analyzed in Figure 4, it is evidently shown that the separation of Alfvénic resonance layers decreases with increase of the shear flow velocity. It is clearly indicated that the closed distance of Alfvénic resonance layers can compress and disturb the current sheet (Figure 6a), but largely suppress the m=1 tearing mode that is the most unstable mode without a shear flow. The compressed current sheet leads to the development of the m=2 tearing mode (Figure 6b). On the other hand, the magnetic islands also modulate the structure of the Alfvénic resonance layers from the m=1 mode to the m=2 mode (Figure 6c). As the islands continue growing, the current density in the Alfvénic resonance layers further intensifies. For the growth of magnetic islands, it is necessary to push the resonance layers away from the reconnection region. Subsequently, the reconnection develops more slowly in the case with strong shear super-Alfvénic flow than with the weak shear super-Alfvénic flow or without shear super-Alfvénic flow.

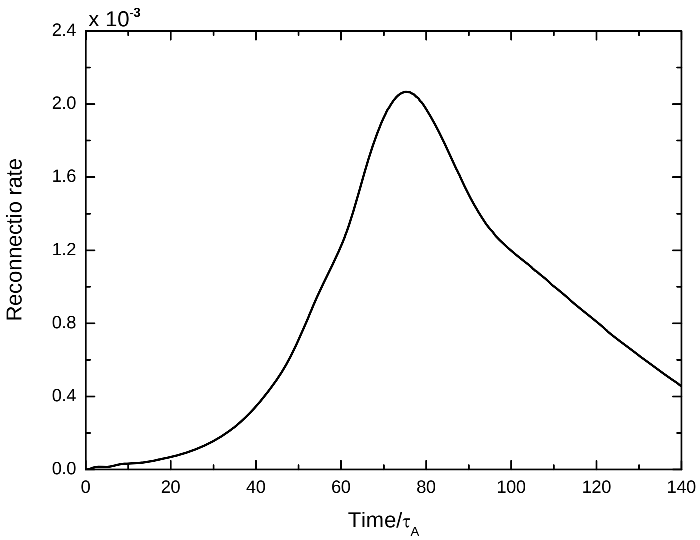

Figure 7. The time evolutions of the reconnection rates for $v_0 = 1.7$ and $a_v = 4a_B$.

Figure 7 show the time evolutions of the reconnection rates for the two islands situation ($v_0 = 1.7, a_v = 0.8$). The two islands appear almost during the rapid growth phase of the magnetic reconnection. The reconnection rate grows fast as the two islands develop, then deceases as the islands gradually saturate. The peak reconnection rate is much smaller than that for the small v_0 cases mainly because the Alfvénic resonance layers are closed to the reconnection current sheet and sufficiently suppress the magnetic reconnection.

B. Effects of shear flow thickness for $v_0 = 1.6$

In this section, we mainly investigate the influence of the shear flow thickness on magnetic reconnection and formation of resonance layers with fixing the shear flow velocity $v_0 = 1.6$.

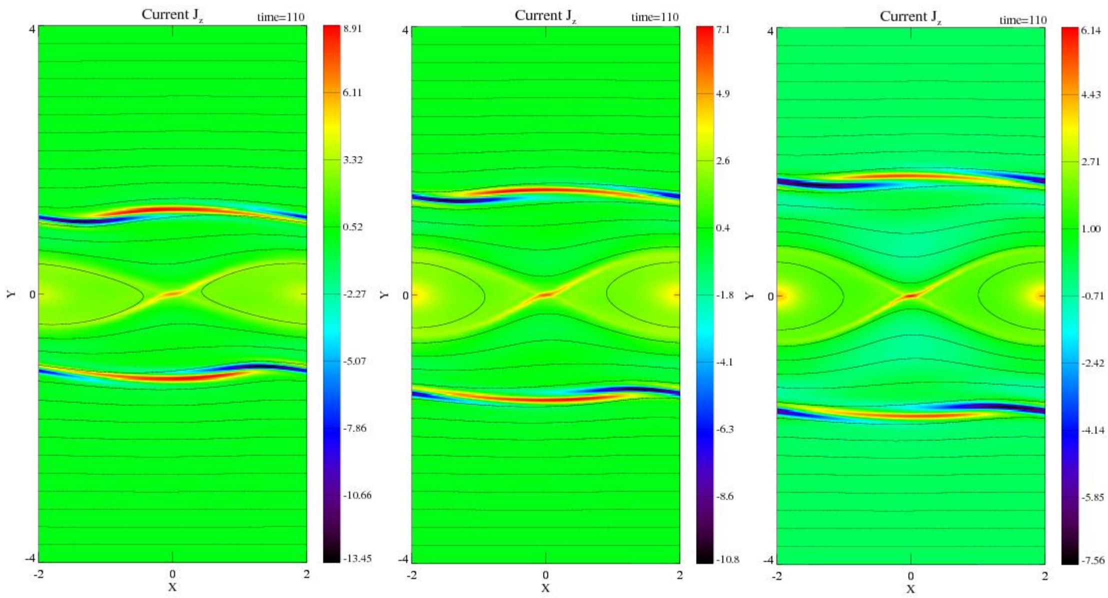

Figure 8. From left to right, locations of Alfvénic resonance layers at the saturated stage for fixing flow velocity ($v_0 = 1.6$) with different shear thickness of $a_v = 0.8$, $a_v = 1.0$, and $a_v = 1.4$, respectively.

Figure 8 shows the same images as figure 4 for varied thickness of shear flow ($a_v = 0.8$, $a_v = 1.0$ and $a_v = 1.4$, respectively) cases with fixed $v_0 = 1.6$ at t=110. From left to right of Figure 8, it is clearly to see the pair of Alfvénic resonance layers tend to move away from each other and the current densities in the Alfvénic resonance layers becomes weaker with the increase of the shear flow thickness. The initial location of the resonance layers become closer to the central current sheet as the decrease of the shear flow thickness or the increase of the initial asymptotic flow velocity as illustrated in Figure 1. It is indicated that the two variables a_v and v_0 have the similar role on the location of Alfvénic resonance layers. As the current intensifications in Alfvénic resonance layers increase and its separation reduces, the size of magnetic island become smaller. Therefore, the magnetic reconnection is suppressed by a strong shear flow with the small a_v cases.

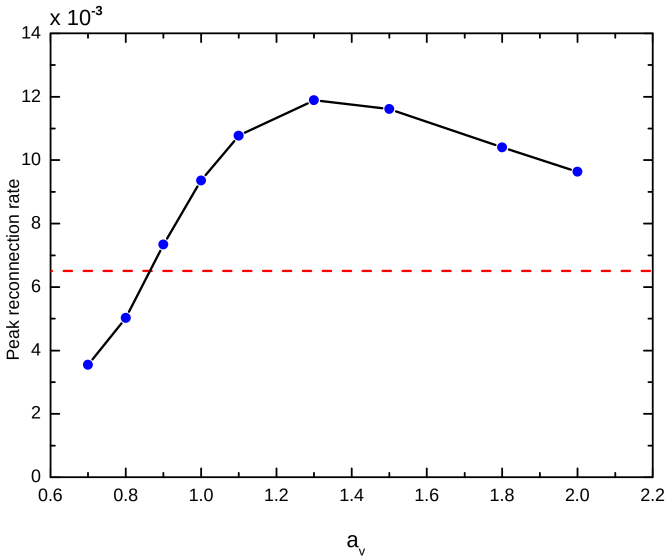

Figure 9. Peak reconnection rates related to different thicknesses of shear flow for $v_0 = 1.6$. The dashed line indicates the peak reconnection rate for case without the shear flow.

Figure 9 shows the influence of different thickness $a_v = 0.7 \sim 2.0$ of the shear flow on peak reconnection rates for $v_0 = 1.6$. It is evident that a threshold for the thickness of the shear flow exists. The peak reconnection rate is greater than that without an initial shear flow, when the thickness of the shear flow is larger than $a_v \sim 0.85$. A maximum of the peak reconnection rate is obtained at $a_v = 1.3$, that is, the boosting effect becomes strongest in this case. The reason why the peak reconnection has such tendency is resulted from the competition between the suppressing effects of Alfvénic resonances and the boosting effect of the Kelvin-Helmholtz instability. The pair of Alfvénic resonance layers is far away from each other with the increase of the thickness, the suppression of magnetic reconnection become weaker, then the peak reconnection rate increases. When the gradient of the shear velocity is weak in the region of the current sheet, the roles of shear flows are gradually disappeared and the results are the same as that without an initial shear flow. As a result, the peak reconnection rate goes down when a_v is larger than 1.3.

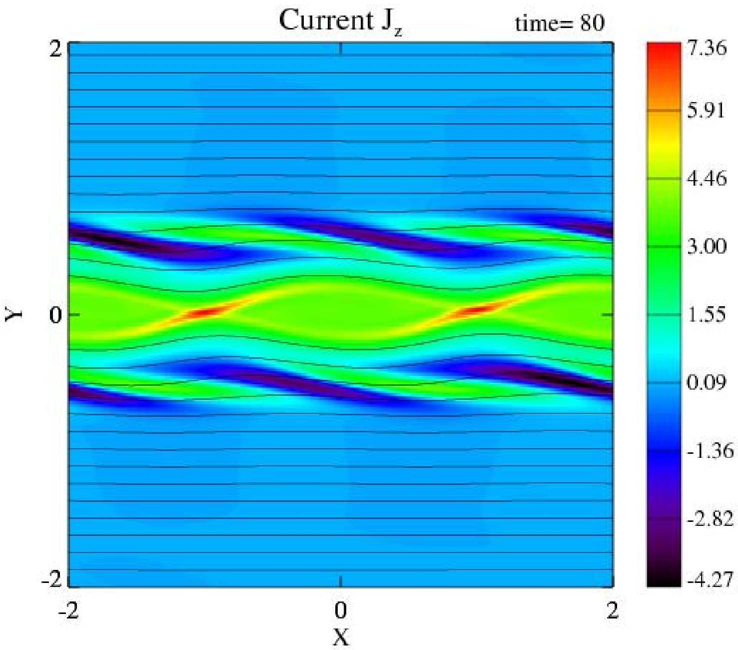

Figure 10. Contour plots of the current density distribution for $v_0 = 1.6$, $a_v = 0.7$ at t=80.

When the thickness of the shear flow is narrow enough, for example $a_v = 0.7$ as shown in Figure 9, the peak reconnection rate is smaller than that without the shear flow. It is clearly seen that the two magnetic islands emerge from the wavy current sheet as shown in Figure 10 because the small separation distance of the resonance layers largely reduces the reconnection rate. The detailed mechanism has already been investigated in the case for $v_0 = 1.7$ and $a_v = 0.8$ in Section 3A. It’s noteworthy that two magnetic islands are generated when the peak reconnection rate is less than that of the case without an initially imposed shear flow.

4. Summary and Discussion

The influences of the super-Alfvénic shear flow on the tearing mode instability are carefully investigated with the resistive incompressible MHD model. It is found that Alfvénic resonance layers can form in the inflow region during the magnetic reconnection in the presence of super-Alfvénic shear flow. The Alfvénic resonance layers are located where the initial shear velocity equals to the local Alfvénic speed and drift away from the current sheet as the magnetic island develops. The intensity of the current density in the Alfvénic resonance layers is determined by the shear strength of the external shear flow, which dependents on the initial asymptotic flow velocity and thickness of the shear flow, and the growth rate of the magnetic island. As the initial asymptotic flow velocity increases or the thickness of the shear flow is reduced, the two Alfvénic resonance layers approach each other and the suppressing effect of Alfvénic resonance layers is strengthened. When the thickness of the shear flow is thicker than that of the current sheet, magnetic reconnection with super-Alfvénic shear flow is mostly controlled by the Alfvénic resonance layers and the Kelvin-Helmholtz instability.

With a fixed thickness of the shear flow $a_v = 0.8$, in the parameter regime of the shear flow velocity below $v_0 = 1.2$, the Kelvin-Helmholtz resistive instability is the dominant process and the growth of magnetic reconnection increases with increase of the flow velocity. As the flow velocity is larger than $v_0 = 1.3$, the presence of the Alfvénic resonance layers mainly shows a suppressing effect on magnetic reconnection, and the peak reconnection rate decreases with increase of flow velocity. When the flow velocity further increases over $v_0 \sim 1.5$, the peak reconnection rate reduce below that without an initially imposed shear flow.

With a given flow velocity, there also exists a threshold for the thickness of the shear flow. The thresholds are different for different velocities of shear flow. For

$v_0 = 1.6$, the threshold is $a_v \sim 0.85$. Below the threshold, the peak reconnection rate is less than that of the case without an initially imposed shear flow and two magnetic islands are usually generated due to formation of Alfvénic resonance layers near the central current sheet.

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