Numerical studies of the Kelvin-Hemholtz instability in a coronal jet

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Abstract Kelvin-Hemholtz (K-H) instability in a coronal EUV jet is studied via 2.5D MHD numerical simulations. The jet results from magnetic reconnection due to the interaction of the newly emerging magnetic field and the pre-existing magnetic field in the corona. Our results show that the Alfvén Mach number along the jet is about 5–14 just before the instability occurs, and it is even higher than 14 at some local areas. During the K-H instability process, several vortex-like plasma blobs with high temperature and high density appear along the jet, and magnetic fields have also been rolled up and the magnetic configuration including anti-parallel magnetic fields forms, which leads to magnetic reconnection at many X-points and current sheet fragments inside the vortex-like blob. After magnetic islands appear inside the main current sheet, the total kinetic energy of the reconnection outflows decreases, and cannot support the formation of the vortex-like blob along the jet any longer, then the K-H instability eventually disappears. We also present the results about how the guide field and flux emerging speed affect the K-H instability. We find that a strong guide field inhibits shock formation in the reconnecting upward outflow regions but helps secondary magnetic islands appear earlier in the main current sheet, and then apparently suppresses the K-H instability. As the speed of the emerging magnetic field decreases, the K-H instability appears later, the highest temperature inside the vortex blob gets lower and the vortex structure gets smaller.

Key words: Sun: corona jet — Kelvin-Hemholtz instability — guide-field — method: numerical simulations

1 INTRODUCTION

A jet that behaves as a transient phenomenon is ubiquitous in the solar atmosphere. It usually appears in an active region or in a polar corona hole. Jets are considered as important mass and energy sources in the upper solar atmosphere and solar wind (Raouafi et al. 2016). They are usually observed in multiple wavelengths, such as Hα, Ca II H, extreme ultraviolet (EUV) and soft X-ray (e.g., Roy & Tang 1975; Shibata et al. 2007; Alexander & Fletcher 1999; Shen et al. 2011; Shibata et al. 1992), and their dynamic, thermal and structural behaviors are different when observed in different wavelengths, which can be used to explore the possible mechanisms associated with the jet. Coronal jets are usually observed in EUV and X-ray wavelengths. Raouafi et al. (2016) summarized the characteristics of coronal jets according to their manifestations, such as velocity, width, height, lifetime and temperature. The temperature of EUV jets ranges from 0.1 to 10 MK, and X-ray jets can be hotter than 10 MK. Moore et al. (2010) classified jets into “standard” and “blow-out” cases according to their morphological features. The spire of a standard jet is narrow during its entire lifetime and the base is relatively dim. A standard jet is modeled by Shibata et al. (1992). The spires of blow-out jets on the other hand become broader with time and eventually reach a size comparable to the width of the jet base, the brightening of the arch base is apparent, and twist and shearing motions usually appear
in the event. Both standard and blow-out jets are considered to result from magnetic reconnection between the emerging new magnetic field and the pre-existing coronal magnetic field.

As the resolution of solar telescopes has improved, many fine structures in jets have been observed. Zhang & Ji (2014) and Zhang et al. (2016) analyzed EUV data from Solar Terrestrial Relations Observatory (STEREO) and the Atmospheric Imaging Assembly on Solar Dynamics Observatory (SDO); they found that bright blobs were produced and ejected out along the jets. The lifetime of these blobs is about 24–60 s, the temperature is between 0.5 MK and 4 MK, and the diameter ranges from 2 to 10 Mm. Zhang & Zhang (2017) recognized multiple upward and downward bright blobs in the legs of jets via studying high-resolution data from the Interface Region Imaging Spectrograph (IRIS). Recently, several observations also showed detailed features in bright blobs associated with coronal jets (e.g. Li et al. 2017; Shen et al. 2017). The mechanism of blob formation in coronal jets is mainly considered to be plasmoid instability (e.g., Bhattacharjee et al. 2009; Ni et al. 2013; Comisso & Bhattacharjee 2016; Nemati et al. 2017) in the magnetic reconnection process. In previous two-dimensional (2D) and three-dimensional (3D) simulations (e.g., Jiang et al. 2012; Yang et al. 2013; Moreno-Insertis & Galsgaard 2013; Wyper et al. 2016) high density magnetic islands or magnetic flux ropes (3D) were found to form in the magnetic reconnection process when the Lundquist number was high enough. These magnetic islands or magnetic flux ropes (3D) are believed to correspond to observed bright blobs.

However, the magnetic island or magnetic flux rope (3D) always merged into the background magnetic fields and the plasma in these simulations, and none of them was observed to be ejected out along the jet as shown in the observational results of Zhang & Ji (2014) and Zhang et al. (2016). For the first time, recent high resolution numerical experiments with high Lundquist number by Ni et al. (2017) indicated that a magnetic island can be easily formed and ejected out along the jet when the plasma $\beta$ is low enough. The characteristics of the magnetic island are similar to those of bright blobs observed in the EUV band. In the case with higher plasma $\beta$, Kelvin-Helmholtz (K-H) instability appeared along the jet and resulted in vortex-like high density and high temperature blobs, which were suggestive of accounting for the bright blobs observed in the EUV band.

K-H instability was found on a shear plane with relative motions between two fluids by Kelvin (1871) and Helmholtz (1868) one and a half centuries ago. However, only a small number of observations have shown K-H instability occurring on the Sun. The irregular evolution of a CME was analyzed by Foullon et al. (2013); they inferred that characteristics of the evolutionary process were consistent with the result of K-H instability. When studying an eruption that started from an active region and produced a CME and flare, Ofman & Thompson (2011) noticed for the first time that the K-H instability occurred in the magnetic configuration of the eruption. They found a set of vortices at the interface between the region where the eruption took place and the nearby region. The sizes of these vortices varied from a few to ten arcseconds and the speed of these features on the interface ranged from 6 to 14 km s$^{-1}$. Ofman & Thompson (2011) identified the vortices as a consequence of K-H instability, which was confirmed by their linear analysis and nonlinear 2.5D magnetohydrodynamics (MHD) numerical experiment. They concluded that it is the velocity shearing between the erupting and nearby stationary magnetic configuration that drove the instability.

Kuridze et al. (2016) found that some of the small-scale structures in the chromospheric jet displayed apparent red and blue shifts in the spectral lines and that the vortex-like structures rapidly appeared along the boundary of the jet. On the basis of the spectral analysis, they found that the chromospheric spectral lines became broader inside these vortex-like and turbulent structures, which could be ascribed to the K-H instability. Zaqarashvili et al. (2015) compared the results of their theoretical model with those of observations, and found that when the jet speed was higher than the Alfvén speed in the jet direction, K-H instability may happen. So far, both theory and observations indicate that the K-H instability does not easily occur in X-ray jets with high speed and low plasma density, but it more easily appears in EUV jets with lower speed and higher plasma density.

Some studies about the basic theories and numerical simulations of K-H instability in the case with magnetic fields along the shearing flows have been reported. In simulations by Jones et al. (1997) and Jeong et al. (2000), the K-H vortices were found to persist until the viscosity and small-scale reconnection dissipated them when the plasma $\beta$ was high enough ($\beta = 3000$ and $\beta = 24 000$) and the magnetic field was weak. Keppens et al. (1999) found that in a uniform magnetic field, the K-H mode grew between two shearing flows with time.
when the Alfvén Mach number $M_A = 9$, but it was stabilized when $M_A = 1.5$.

Tian & Chen (2016) numerically explored K-H instability in the case of different magnetic fields imposed in the direction of the two shearing flows. The results showed that dynamic behaviors of the plasma fluid change with Alfvén Mach number in the direction of the fluid velocity. The K-H mode was linearly stabilized for $M_A \leq 2.27$; the K-H mode was nonlinearly stable and developed into wavy motions for $2.27 \leq M_A \leq 2.8$; in the range of $2.8 \leq M_A \leq 6.2$, the K-H mode was unstable and evolved into filamentary flows; the K-H vortex can fully roll up in an even higher $M_A$, e.g., $M_A = 50$, but the small-scale reconnection would destroy the K-H instability soon. K-H instability has not been identified in previous coronal EUV jet simulations except for the work by Ni et al. (2017). In this investigation, we study K-H instability in a solar coronal jet with different guide fields based on the previous 2D work by Ni et al. (2017). The effects of guide-field and flux emerging speed on the jet formation and K-H instability process will be presented. The numerical model is described in Section 2. We will present our numerical results in Section 3. In the last section, we will summarize this work.

2 NUMERICAL MODEL

The single-fluid MHD equations including gravity and thermal conduction are given below:

\[
\begin{align*}
\partial_t \rho &= -\nabla \cdot (\rho v), \\
\partial_t B &= \nabla \times (v \times B - \eta \nabla \times B), \\
\partial_t (\rho v) &= -\nabla \cdot \left[ \rho vv + \left( p + \frac{1}{2\mu_0} |B|^2 \right) I \right] \\
&\quad + \nabla \cdot \left( \frac{1}{\mu_0} BB \right) + \rho g, \\
\partial_t e &= -\nabla \cdot \left[ \left( e + p + \frac{1}{2\mu_0} |B|^2 \right) v \right] \\
&\quad + \nabla \cdot \left( \frac{1}{\mu_0} (v \cdot B) B \right) \\
&\quad + \nabla \cdot \left( \eta \frac{1}{\mu_0} B \times (\nabla \times B) \right) \\
&\quad - \nabla \cdot F_C + \rho g \cdot v, \\
e &= \frac{p}{\rho} + \frac{1}{2} |v|^2 + \frac{1}{2\mu_0} |B|^2, \\
p &= \frac{2\rho}{m_i} k_B T.
\end{align*}
\]

Here, $\rho$, $v$, $e$, $B$ and $p$ represent the plasma density, velocity, total energy density, magnetic field and gas pressure, respectively. $F_C$ is the flux of the thermal conduction, $g = -273.9 \text{ m s}^{-2}$ is the constant acceleration of gravity of the Sun. In this work, we use the international system of units (SI) for all variables.

The initial background magnetic field is set as $B_{x0} = -0.6b_0$ and $B_{y0} = -0.8 b_0$ ($b_0 = 0.0015 \text{ T}$). In this work, we have added different guide fields in the $z$-direction for four cases: $B_{z0} = 0.05 b_0$ in Cases I, III and IV and $B_{z0} = b_0$ in Case II. The initial plasma velocity is zero, and the initial temperature is $T_0 = 8 \times 10^5 \text{ K}$. The initial stratified density including constant acceleration of gravity is given as

\[
\rho_0 = \rho_{00} \exp \left( -\frac{m_i g}{2 k_B T_0} y \right),
\]

where $\rho_{00} = 0.5 \times 1.66057 \times 10^{-10} \text{ kg m}^{-3}$, the mass of a proton is $m_i = 1.66057 \times 10^{-27} \text{ kg}$ and the Boltzmann constant is $k_B = 1.3806 \times 10^{-23} \text{ J K}^{-1}$. The simulation box is inside the domain $0 < x < 200 L_0$ and $0 < y < 100 L_0$, with $L_0 = 10^6 \text{ m}$.

We use temperature-dependent magnetic diffusivity in all the four cases

\[
\eta = 10^8 \frac{(T_0/T)^{3/2} + 10^{9.05} \left[ 1 - \tanh \left( \frac{y - 2 L_0}{0.2 L_0} \right) \right]}{J K \text{ s}^{-1}},
\]

Unit of $\eta$ is $\text{m}^2 \text{s}^{-1}$. The anisotropic heat conduction flux, $F_C$, is given by (e.g., see also Spitzer 1962)

\[F_C = -\kappa_\parallel \left( \nabla T \cdot \hat{B} \right) \hat{B} - \kappa_\perp \left[ \nabla T - \left( \nabla \cdot \hat{B} \right) \hat{B} \right],\]

where $\hat{B} = B / |B|$ is the unit vector in the direction of the magnetic field. The parallel and perpendicular thermal conductivity ratios, $\kappa_\parallel$ and $\kappa_\perp$ respectively, are given by

\[
\kappa_\parallel = \frac{1.84 \times 10^{-10}}{\ln \Lambda} T^{5/2},
\]

\[
\kappa_\perp = \min(\kappa_\perp', \kappa_\parallel),
\]

with

\[
\kappa_\perp' = 8.04 \times 10^{-33} \left( \frac{\ln \Lambda}{m_i} \right)^2 \frac{\rho^2}{T^3 B^2} \kappa_\parallel,
\]

where $\ln \Lambda = 30$, and the unit for $\kappa_\parallel$ and $\kappa_\perp$ is $\text{J K}^{-1} \text{ m}^{-1} \text{ s}^{-1}$.

We use the NIRVANA code to solve Equations (1) through (11) in this work. This code has been clearly described in previous works (e.g., Ziegler 2008, 2011; Ni et al. 2017). The adaptive mesh refinement method in this simulation is the same as in the paper by Ni et al. (2017), the base-level grid is $320 \times 160$ and the highest refinement level is 10. All the pictures presented in this work
are also plotted by using level 3 or level 4 uniform IDL data, which are transformed from the original raw data.

Two extra layers with the ghost grid cell are applied to the code to set boundary conditions at each boundary. The boundary conditions are the same as in the previous paper by Ni et al. (2017) except that we also need to set boundary conditions for magnetic field and velocity in the $z$-direction in this work. The outflow boundary conditions as described in Ni et al. (2017) are applied at the left ($x = 0$), right ($x = 200L_0$) and upper ($y = 100L_0$) boundaries. The condition of being divergence-free for the magnetic field requires continuity in the normal component of the magnetic field on the boundary, which can be used to extrapolate the normal component through the boundary. We also insert two ghost layers below the physical bottom boundary $y = 0$. The gradient of the plasma velocity vanishes at the bottom boundary. The magnetic field inside the two layers with the ghost grid cells is set as:

$$b_{zb} = -0.6b_0 + \frac{100L_0(y - y_0)b_1 f}{(x - x_0)^2 + (y - y_0)^2} \left[\tanh\left(\frac{x - 70L_0}{\lambda}\right) - \tanh\left(\frac{x - 130L_0}{\lambda}\right)\right],$$

$$b_{yb} = -0.8b_0 - \frac{100L_0(x - x_0)b_1 f}{(x - x_0)^2 + (y - y_0)^2} \left[\tanh\left(\frac{x - 70L_0}{\lambda}\right) - \tanh\left(\frac{x - 130L_0}{\lambda}\right)\right],$$

where $f = t/t_1$ for $t \leq t_1$ and $f = 1$ for $t \geq t_1$,

$x_0 = 100L_0$, $y_0 = -12L_0$, $b_1 = 3 \times 10^{-4} T$ and $

\lambda = 0.5L_0$ with $t_1 = 500 \text{ s}$ for Cases I and II, $t_1 = 700 \text{ s}$ for Case III, and $t_1 = 350 \text{ s}$ for Case IV. We set the magnetic field in the $z$-direction in the bottom ghost grid cells $b_{zb}$ to be equal to the initial value of the magnetic field in the $z$-direction inside the computational domain, $b_{zb} = B_{z0}$. When $t < t_1$, the strength of the magnetic field below the bottom boundary varies with time, and flux emergence stops after $t = t_1$. As shown previously by Forbes & Priest (1984), Chen & Shibata (2000) and Ding et al. (2010), one can set up the magnetic flux emergence by changing the conditions with time at the bottom boundary. As described by Ni et al. (2017), the magnetic field does not satisfy the divergence free condition $\nabla \cdot \mathbf{B} = 0$ inside the two ghost layers around $x = 70L_0$ and $x = 130L_0$. The high magnetic diffusion below $y = 0.2L_0$ as shown in Equation (8) can smooth the non-physical features inside the two ghost layers, then the related values at the bottom boundary are smoothed.

3 NUMERICAL RESULTS

3.1 K-H Instability in a Coronal Jet with a Guide Field

Case I and Case II differ from each other in the guide field. The guide field is $B_{z0} = 0.05b_0$ for Case I, and $B_{z0} = b_0$ for Case II. In Figures 1 and 2 we can see the distribution of the current density in $z$-direction $J_z$, the temperature $T$, the plasma density $n$, and the velocity along the jet direction $v_||$ and the distributions of the emission count rate in the AIA 211 Å channel at five different times in Cases I and II, from which we can see the jet’s evolutionary process in the two cases after the emergence of magnetic field stops. The distributions of each variable in Case I as shown in Figure 1 are almost the same as those displayed in figure 7 of Ni et al. (2017). The jet lifetime is about 37 min, the jet maximum temperature is about 1.8 MK and the maximum velocity along the jet direction is 320 km s$^{-1}$.

In Case II, the jet lifetime is about 33 min, the maximum temperature is 1.6 MK and the maximum velocity along the jet direction is 275 km s$^{-1}$, which are smaller than the corresponding parameters in Case I. In Figure 3, we present the maximum velocities along the jet direction at each time step in all the four cases. One can see that there is an apparent peak in Cases I, III and IV with a weak guide field. These peaks appear after the K-H instability starts and before the magnetic island appears in each of these cases. However, there is no apparent peak in Case II with a strong guide field. The maximum velocity along the jet direction in Case II is also slightly smaller than that in Case I after K-H instability appears. We notice that the characteristics of the simulated jets here are consistent with those shown by EUV observations of coronal jets (see Raouafi et al. 2016).

In Figures 1 and 2, we can see clearly that the vortex-like blobs with high density and high temperature are rolled up in the jet. The vortex-like structure of the plasma blob at the bottom of the jet is more apparent than those along higher positions of the jet. The higher the plasma blob is, the less the blob is rolled up. As pointed out by Ni et al. (2017), these vortex-like blobs indicate strong shearing flows between the surrounding plasma and jet, which leads to the K-H instability. Based on the previous theory and simulations (e.g., Keppens et al. 1999; Tian & Chen 2016), the K-H instability can be suppressed by the magnetic field along shearing layers, and
Fig. 1 Distributions of different variables at five different times in Case I: (a) current density, $J_z$, (b) temperature, $T$, (c) logarithm of plasma number density $\log n$, (d) velocity along the jet direction $v_{||, \text{max}}$ and (e) distributions of the emission count rate in the AIA 211 Å channel at five different times in Case I. Continuous black curves represent the magnetic fields and the black arrows represent the velocity vector in each panel.
Fig. 2 Same as Fig. 1 but for Case II.
it can only appear when the Alfvén Mach number along the shearing layers is high enough.

Figure 4 shows the distribution of velocity $v_{||}$ and the corresponding Alfvén Mach number $M_A$ at $t = 784.3$ s before the K-H instability happens. $v_{||}$ is the plasma velocity along the jet direction. From Figure 4, we can find that the jet direction is roughly the same as the direction of the initial background magnetic fields in the $xy$-plane at $t = 784.3$ s, though the maximum of $v_{||}$ is only 265 km s$^{-1}$, which is still larger than the corresponding Alfvén velocity $v_{A||}$ along the jet. The Alfvén Mach number along the jet direction is defined as $M_A = v_{||}/v_{A||}$ (e.g., Keppens et al. 1999; Tian & Chen 2016), and the value of $M_A$ is between 5 and 14 in most regions inside the jet. In this work, we use the strength of the magnetic field component which is parallel to the jet direction to calculate the Alfvén speed $v_{A||}$. From Figure 4 we can also find that $M_A$ is apparently larger than 14 at some local areas; the magnetic fields are strongly folded and almost perpendicular to the jet direction at these areas. Therefore, the Alfvén velocity $v_{A||}$ along the jet is close to zero and $M_A$ is very large in these areas.

Keppens et al. (1999) studied the K-H instability by using different initial magnetic configurations around the shearing flows. In the cases that parallel magnetic fields at both sides of the flows possess the same orientation, they found that the K-H instability grew with time when the initial Alfvén Mach number was $M_A = 9$, and it was stabilized when the magnetic field was strong and $M_A = 1.5$. Tian & Chen (2016) concluded that the K-H mode was unstable and evolved into filamentary flows when $2.8 \leq M_A \leq 6.2$, but the K-H vortex can fully roll up only for a very large value of $M_A$, say $M_A = 50$. In both papers, $M_A$ was calculated by using the initial flow velocity and Alfvén velocity along the direction of shearing flows.

Comparing our analysis in the previous paragraphs with their results, we find that the value of $M_A$ in the jet region in our simulations is always big enough to trigger the K-H instability. But this value is not big enough in most areas in the case shown in Figure 4 to fully roll-up the plasmas, especially in regions near the top of the jet. Tian & Chen (2016) also found that the small scale reconnections between the rolled-up magnetic fields would destroy vortex-like structures soon after the vortex structures were formed, even for a large $M_A$. We notice as well many small scale current sheet fragments due to magnetic reconnection inside the vortex-like blobs, as displayed in Figures 1 and 2, which also play a role in destroying the vortex blobs. The appearance of these vortex-blobs lasts for about 8 min in Case I and about 6 min in Case II.

Zaqarashvili et al. (2015) analyzed and derived the critical conditions for K-H instability in both the axial and azimuthal directions of the jets. Based on observation results and their theoretical models, they studied the possibilities for generating K-H instabilities in macrospicules, type II spicules, X-ray coronal jets and EUV jets. They concluded that the K-H instability is more likely to appear in a higher density and lower speed EUV jet, and the K-H instability can occur along the EUV jet with plasma density up to $10^{16} - 10^{17}$ m$^{-3}$ and velocity of 250 km s$^{-1}$ when the axial magnetic field is about 10 G and the Alfvén speed reaches 220 km s$^{-1}$. For comparison, we listed several important parameters with the corresponding characteristic values obtained in this work and by Zaqarashvili et al. (2015) in Table 1. We notice that the results deduced by these two works are consistent with one another.

From Figures 1, 2, 5 and 7, we can see that the reconnection outflows in the main current sheet and the vortex-like structures are very different from one another in Cases I and II. The plasma velocity divergence $\nabla \cdot v$ reflects the compression degree of the plasma. From the distributions of $\nabla \cdot v$ in the simulation domain, we can preliminarily judge if the shock structure appears or not (Ni et al. 2017; Nóbrega-Siverio et al. 2016). We have analyzed the distributions of $\nabla \cdot v$ at different times in Cases I and II. In addition to the intermediate shock at shock front SF1 as shown in Figure 5, we have recognized two fast mode shocks at shock front SF2 and shock front SF3 in the outflow region of the main current sheet in Case I with a weak guide field. We only find the intermediate shock at shock front SF1 in the whole evolution process of Case II with a strong guide field, and no fast mode shock appears.

We have used the MHD jump conditions as presented below (e.g., see also Ni et al. 2017) to analyze these shocks and judge the type of shocks. In MHD jump conditions (e.g., see also Priest 2014)

\begin{align}
B_{n1} &= B_{n2}, \\
\rho_1 v_{n1} &= \rho_2 v_{n2}, \\
\rho_1 v_{n1}^2 + p_1 + \frac{B_{n1}^2}{2\mu_0} &= \rho_2 v_{n2}^2 + p_2 + \frac{B_{n2}^2}{2\mu_0},
\end{align}

where subscript $t$ represents the component which is tangential to the shock front, subscript $n$ represents the component that is normal to the shock front, and properties
Fig. 3 The maximum velocities along the jet direction versus time for the four cases.

Fig. 4 Distributions of the velocity (a) and $M_A$ (b) along the jet direction for Case I at $t = 784.3\text{ s}$.

Fig. 5 Distributions of the velocity divergence (a) and temperature (b) in the reconnection outflow region of the main current sheet at $t = 801.7\text{ s}$ in Case I; the same for Case II in panels (c) and (d) at $t = 794.8\text{ s}$.
Table 1 Comparison of values for some important parameters studied by Zaqarashvili et al. (2015) and by us in Case I. Our results are selected at $t = 784.3$ s in the simulation just before the K-H instability takes place. Both the jet speed and the Alfvén speed are along the jet direction.

| Parameters          | Zaqarashvili’s | Case I (average) | Case I (maximum) |
|---------------------|----------------|-----------------|-----------------|
| Magnetic field (G)  | 10             | 5               | 15              |
| Alfvén speed (km s$^{-1}$) | 220            | 50              | 250             |
| Jet speed (km s$^{-1}$) | 250            | 160             | 265             |
| Density ($m^{-3}$)  | $10^{16} - 10^{17}$ | $2.8 \times 10^{16}$ | $5 \times 10^{16}$ |
Fig. 7. The distribution of velocity vector, current density $J_z$, logarithm of plasma number density $\lg n$ and temperature $T$. Panels (a), (b), (c) and (d) are for Case I at $t = 1082$ s; and panels (e), (f), (g) and (h) are for Case II at $t = 1079$ s.

ahead of and behind the shock are denoted by 1 and 2 respectively. From Figure 5(a) and (b), we can see that the plasma is sharply heated to high temperatures behind the two fast mode shocks in Case I, but no fast mode shock occurs in Case II. However, heating that was probably caused by the compression and Joule dissipation can also be noticed (Fig. 5(c) and (d)).

In both Cases I and II, the vortex-like structures start to break after the magnetic islands appeared in the main current sheet as shown in Figures 1 and 2. Figure 6 shows how the vortex-like structures change before and after magnetic islands become visible. One can find that the vortex-like blobs start to move toward the left bottom and break after the magnetic islands appear.

Figure 6(b) shows the distribution of kinetic energy along the jet direction at different times. As multiple reconnection X-points and magnetic islands are apparent in the main current sheet, the upward reconnection outflow velocity and the corresponding kinetic energy gradually decrease. When the outflows cannot provide enough kinetic energy to push the high density vortex-like blobs upward along the jet, these vortex-like blobs start to fall down. So, in addition to small scale magnetic reconnection inside the vortex like blob, magnetic islands appearing in the main current sheet are another important reason that causes the K-H instability to disappear.

As displayed in Figure 6(b), the thick lines NL1 and NL2 are located along the current sheet direction at $t = 1041.3$ s before magnetic islands appear and after magnetic islands appear at $t = 1294$ s, respectively. Figure 6(c) and (d) shows the distributions of plasma velocity along NL1 and NL2, indicating that the outflow velocity apparently decreases after magnetic islands appear. In the turbulent reconnection process many magnetic islands of different sizes, together with the X-points, occur inside the current sheet (e.g., see also Bhattacharjee et al. 2009; Bártá et al. 2011; Shen et al. 2011; Mei et al. 2012; Ni et al. 2015). The reconnection outflow bifurcates at
the X-point, which makes the different sizes of magnetic islands connecting to the nearby X-point have different velocities (some of them even have opposite velocities). Therefore, these islands collide and coalesce with one another, and their motions spontaneously slow down. This issue has also been discussed previously (e.g., see Innes et al. 2015).

As exhibited in Figure 7, three vortex-like blobs could be recognized clearly in Case I, but only two obvious vortex-like blobs are identified in Case II. Comparing Figure 1 with Figure 2, we notice that the magnetic island does not appear yet in the main current sheet at \( t = 1186.7 \text{s} \) in Case I, but several magnetic islands are already visible in the main current sheet at the same time in Case II. Magnetic islands in the main current sheet of Case II are apparent about 3 min earlier than those in Case I. Therefore, the third vortex-like blob that was supposed to appear at the top of the jet in Case II did not show up before the two vortex-like blobs at the lower position had already been destroyed.

In order to compare with observations and previous results (Ni et al. 2017), we calculate the temperature and density dependent emission count rate; the emission count rate is calculated as \( \text{ECR} = \int n^2 f(T) dl \text{DN s}^{-1} \text{pixel}^{-1} \), where \( f(T) \) is the AIA 211 Å response function, \( n \) is the number density and \( dl \) is the line element along the line of sight (e.g. see also Ni et al. 2013). From the AIA synthetic EUV images shown in Figure 1(c), we can see that there are three obvious vortex-like bright blobs at \( t = 1044.8 \text{s} \) and \( t = 1186.7 \text{s} \) in Case I with a weak guide field, which are similar to those shown by Ni et al. (2017). As displayed in Figure 2(e), the vortex-like blobs are less obvious and we can only identify two bright blobs caused by the K-H instability in Case II with a strong guide field.

Ni et al. (2013) investigated the impact of a guide field on the reconnection process. They demonstrated that different guide fields result in different critical values of the Lundquist number. Magnetic islands can only appear when the Lundquist number exceeds such a critical value. Including a guide field in the reconnection region changes the distributions of plasma and magnetic pressures. The results of this work indicate that the main current sheet reaches the critical Lundquist number earlier in the case with a strong guide field. The shock structures obviously appear in the upward outflow regions of the main current sheet in Case I with a weak guide field, but no apparent shock structure is found in Case II with a strong guide field. It is the influence of guide field on the reconnection process as discussed above that causes the K-H instability and the vortex-like blobs to form in different fashions.

### 3.2 Impact of the Flux Emerging Speed on the Jet and K-H Instability

The important parameters in this work are listed in Table 2. The guide field used in Cases I, III and IV is the same, but the emerging times in these cases are different. The total emerging time in Case III is 700 s, in Case I it is 500 s and it is only 350 s in Case IV. Therefore, the flux emerging in Case IV is faster than that in Case I, and the flux emerging in Case III is the slowest one.

Figure 8 shows the variations of electromagnetic energy emerging through the bottom boundary versus time in Cases I, III and IV. The value of \( P_E \) is calculated as \( P_E(t) = \iint P(x, 0, t) \cdot dS_{xz} \), where \( P(x, 0, t) \) is the Poynting flux vector through the bottom boundary and \( dS_{xz} \) represents the area at the bottom boundary. The direction of \( dS_{xz} \) is along the \( y \)-axis. Since all the variables are only functions of \( x \) and \( y \) in space and they do not change along the \( z \)-axis, we then assume \( dS_{xz} = dx l_z \hat{e}_y \) and \( l_z = 100 L_0 \). From Figure 8, we notice that the energy emerges fastest in Case IV and the corresponding maximum of \( P_E \) is also the largest among the three cases.

From Table 2, we notice that the jet lifetime in Case III is about 40 min which is the longest in all the cases. As shown in Figure 3, the maximum velocity along the jet direction in Case III is \( 295 \text{ km s}^{-1} \), which is slower than that in Case I. The highest temperature in Case III is \( 1.7 \text{ MK} \), which is slightly lower than that in Case I. The vortex-like blobs start to form at \( t = 950 \text{s} \) in Case III, about 150 s later than in Case I. Magnetic islands in the main current sheet of Case III start to appear at \( t = 1310 \text{s} \), 60 s later than in Case I. We also find that the jet lifetime in Case IV is about 32 min, the shortest one in all the cases. The maximum velocity along the jet direction is \( 335 \text{ km s}^{-1} \), which is a little bit faster than that in Case I. The maximum temperature in Case IV is \( 2.2 \text{ MK} \), which is higher than in Case I. The vortex-like blobs start to form at \( t = 750 \text{s} \), 50 s earlier than in Case I, and the magnetic islands appear at about \( t = 1190 \text{s} \), 60 s earlier than in Case I. Figure 3 also indicates that the maximum velocity along the jet direction is slower when the flux emerging speed is slower before the K-H instability initiates.
Comparing various features and behaviors of magnetic configurations in the three cases, we realize that the slower the emerging speed of the magnetic field is, the longer the lifetime of the jet is, and the later the vortex-like blobs and the magnetic islands in the main current sheet appear. A slower emerging speed yields a lower maximum speed and lower maximum plasma temperature. From Figure 9, we can also see that the smaller vortex-like structures result from slower emerging speed.

4 CONCLUSIONS

On the basis of the 2D MHD coronal jet simulations by Ni et al. (2017), we included a guide field in the $z$-direction in this work to investigate the response of the coronal jet to the new emerging flux. Detailed analysis of the K-H instability and comparisons with previous works have been conducted. We have also studied the effect of the guide field and flux emerging speed on jet formation and K-H instability. The main conclusions from our numerical simulations are as follows:

(1) For the coronal EUV jet with plasma density in the range from $6 \times 10^{15}$ to $5 \times 10^{16} \text{ m}^{-3}$ and maximum values of magnetic field of 15 G and jet speed of 265 km s$^{-1}$, the Alfvén Mach number reaches 5–14 along the jet direction. The K-H instability can take place in such an EUV coronal jet. Our numerical re-
sults confirm the theoretical model and speculations about results from Zaqarashvili et al. (2015).

(2) The vortex-like blobs are destroyed as a result of the small-scale reconnection processes among the rolled-up magnetic field inside these blobs, as well as the slowing down of upward reconnection outflow from the main current sheet after magnetic islands appear. A strong guide field changes the reconnection outflow pressure balance structures to prevent an apparent shock structure from being invoked, but helps magnetic islands appear earlier than in the case without a guide field or with a weak guide field, which further prevents the occurrence of K-H instability and vortex-like blob.

(3) The speed of the newly emerging flux affects the occurrence and development of K-H instability as well. With other parameters describing the environment being given, the faster the flux emerges, the shorter the lifetime of the jet is, the higher the speed and the maximum temperature of the jet are, the earlier the magnetic island in the main current sheet and the K-H instability occur, and the larger and hotter the vortex-like structures are.

In this work, the guide field is imbedded in the magnetic configuration of interest, and variations of several important parameters, as well as their associated behaviors in the coronal jet system in 2.5D, have been investigated. We expect to perform true 3D numerical experiments in the future to investigate the formation of the flux rope (the counterpart of the magnetic island in 2D) in the main current sheet, and further study the K-H instability in the poloidal direction as a result of the rotation of the jet.

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| Case | $t_1$ (s) | $b_z$ | $t_{life}$ (min) | $v_{||_{max}}$ (km s$^{-1}$) | $t_v$ (s) | $t_i$ (s) | $T_{max}$ (MK) |
|-----|----------|------|----------------|-----------------|---------|--------|--------------|
| I   | 500      | 0.05$b_0$ | 37             | 320             | 800     | 2      | 1250         | 1.8        |
| II  | 500      | $b_0$    | 33             | 275             | 850     | 2      | 1080         | 1.6        |
| III | 700      | 0.05$b_0$ | 40             | 295             | 950     | 3      | 1310         | 1.7        |
| IV  | 350      | 0.05$b_0$ | 32             | 335             | 750     | 3      | 1190         | 2.2        |

Notes: $b_0$ is the initial background magnetic field, $t_{life}$ is the lifetime of the jet, $v_{||_{max}}$ is the maximum velocity along the jet direction, $t_v$ is the time when the vortex structure starts to appear, $t_i$ is the time when the magnetic island starts to appear, $N$ is the number of vortex structures and $T_{max}$ is the maximum temperature in the jet.
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