Effect of the Inclination Angle on Premixed Flame Dynamics in Half-Open Ducts

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ABSTRACT: The propagation of premixed methane/air flames in long half-open ducts with different inclination angles \( \theta \) between the sidewall and the horizon was numerically investigated using the laminar model. The numerical result was compared with the experimental and theoretical ones to validate the numerical model. The results show that the numerical results are in good agreement with them. The investigation provides the basic understanding of the effects on changing the shape of the ducts to promote the premixed flame combustion. For methane/air, the position where the flame front begins to concave is pushed back with the increase in angle \( \theta \). The so-called "tulip" flame even disappeared, if the angle \( \theta \) is bigger than one certain value. Moreover, the flame propagation speed and pressure are enhanced as the angle \( \theta \) increases. In addition, the numerical simulation indicates that the burning gas creates an eddy near the tip of the flame, altering the flow field and causing the tulip flame to appear. However, with the angle \( \theta \) increased, the flame propagation is restrained by the change in sidewalls, resulting in the different flow patterns to suppress the formation of tulip flames and promote flame combustion.

1. INTRODUCTION

As the global economy develops so rapidly, many problems have become more and more serious such as global warming, melting glaciers, and air pollution, which make it important to exploit clean fuel. Now, methane is widely distributed in nature, and it is the simplest organic matter, broadly employed in industry as a clean gas, and can be used to produce acetylene, hydrogen, and so forth.\(^1\) In industrial applications, most explosion accidents result from a flammable combination releasing massive rapid energy, which results in the most destructive manner, detonation-to-deflagration transition (DDT).\(^2-5\) Thus, it can be seen that the safety mainly depends on its explosion characteristics. Therefore, it is in urgent need of performing research on the explosion behaviors of \( \text{CH}_4/\text{air} \) mixtures, helping to reduce the safety risks of industrial transport and use of methane.

In the last few decades, extensive research studies have been performed to characterize the flame propagation on gas explosions.\(^6,6-8\) The combustion characteristics of premixed flame, related to the safety applications, are generally studied in a horizontal duct, affected by many other parameters, for example, the inert gas, the igniter geometry, the aspect ratio of the tube, the equivalence ratio, boundary conditions, obstacles, and so forth.\(^7-11\) Many combustion models were investigated and used to compare the premixed flame structure and pressure with the experimental results.\(^12-15\) Among these studies, a flame could show various shapes, and the most interesting and attractive flame shape is a tulip flame discovered by Ellis\(^16\) and named by Clanet and Searby.\(^15\) It is necessary to experience four classic stages to form. After ignition, the flame spreads spherically first and then develops into a finger shape, and the flame surface area accelerates exponentially. The finger flame grows until the flame skirt touches the sidewalls; meanwhile, the acceleration process stops, followed by flame front inversion, presenting the classical tulip flame. There are massive literature reports on the mechanisms and hypotheses of the inversion of the planar flame.\(^5,17,18\) However, because of the complexity of the forming process, it is still not clearly defined. Currently, more research has laid emphasis on the possible factors affecting the flame formation of tulips, neglecting to explore the underlying mechanism. The creation of the "tulip" flame has been visualized and explored by Ponizy et al.,\(^17\) finding that the
“tulip” flame is just a sheerly hydrodynamic phenomenon, unrelated to the Rayleigh–Taylor and Richtmyer–Meshkov instabilities. Although many experiments have been carried out to explore the mechanism of tulip flame formation, some parameters still need to be simulated to explain. Parallel computing greatly reduces the processing time of data sets, so the numerical simulation of flame propagation in pipelines has caused concern. Numerical simulation can provide more useful parameters for understanding the mechanism of flame propagation than experiments, such as the pressure dynamics of the flame structure, flow field near the flame, and so on.

In this work, the propagation of CH$_4$/air flames in long half-open ducts with different angles $\theta$ between the sidewall and the horizon was numerically investigated using the model of viscous adopting laminar. Seven computational domains with different angles were calculated. The numerical result when $\theta = 0$ was compared with the experimental and theoretical outcomes to validate the numerical model. The results show that the numerical results are in good agreement with them. This study aims to explain the knowledge of the suppression of tulip flame formation and enhancement of the flame by changing the angle $\theta$ of the duct.

2. NUMERICAL METHODS

Premixed combustion is a typical chemical process of heating and mass transfer. The premixed flame spreads in a laminar flow, which is validated. Therefore, the model of viscous adopts the laminar flow model numerically.

Many studies have well proved that the spread of the premixed flame could be positively stimulated by the 2D numerical method, and the reproduced planar flame and following inversion of the flame tip are fairly well matched with the experimental results. Therefore, the present paper used a 2D laminar flow model to simulate the effect of the inclination angle on premixed flame dynamics in half-open ducts. Assuming that the reactants in the closed pipe are completely premixed, we set it as an ideal gas. The governing equations of conservation equations for mass, momentum, energy, and species are shown below

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$$

(1)

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \frac{\partial}{\partial x_i} \sigma_{ij} \right)$$

(2)

$$\sigma_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial}{\partial x_i} \delta_{ij}$$

(3)

where $k$ is the coefficient of heat conduction, $t$ is the time, $p$ is the pressure, $T$ is the temperature, $u_i$ is the speed of component, $\mu$ is the viscosity, $Q_c$ is the heat source produced by internal chemistry, $\rho$ is the density of the premix gas, and the internal energy and the stress tensor of the premix gas are $e = h - \frac{p}{\rho} + \frac{u_i^2}{2}$ and $\delta_{ij}$ respectively. $D_m, J_m, Y_m, h_m$, and $\delta_m$ are the parameters of diffusivity, diffusion flux, the fraction of mass, constant enthalpy, and reaction rate of $m$, correspondingly. Moreover, $p = \rho RT$ because the premix gas is regarded as the ideal gas, where $R$ is the gas constant.

Figure 1 shows that the uniform structured grid is adopted with the grid size 0.5 × 0.5 mm, refining the ignition area grid several times. According to the temperature gradient, a mesh adaptive method is used to refine the flame surface automatically, making the calculation more accurate. The angle $\theta$ between the left wall and the sidewalls is changed from 0 to 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6$^\circ$, but in order to keep energy conservation to make the 2D numerical simulation area equal, the values of $x$ and $y$ also change, as shown in Table 1, as $\theta$

| $\theta$ (deg) | $y$ (mm) | $x$ (mm) | $S$ (mm$^2$) |
|--------------|--------|--------|--------|
| 0            | 1000.000 | 25.000 | 25,000 |
| 0.1          | 1037.572 | 23.189 | 25,000 |
| 0.2          | 1081.685 | 21.224 | 25,000 |
| 0.3          | 1134.870 | 19.058 | 25,000 |
| 0.4          | 1201.600 | 16.610 | 25,000 |
| 0.5          | 1290.815 | 13.731 | 25,000 |
| 0.6          | 1425.770 | 10.070 | 25,000 |
boundary. Because the reactants and products are the same, if the thermodynamic parameters are kept the same, the equilibrium temperature will not change. Set the ignition temperature to the appropriate equilibrium value 2320 K. The setting of the time step is mainly based on the cell Courant number, which is exactly limited below 0.7. Quiescent initial conditions were used with velocity components set to zero everywhere. The component concentration within the ignition radius was set to the value at equilibrium.

3. EXPERIMENTAL SETUP

The self-built premix explosion experimental device is shown in Figure 2, which is composed of the plexiglass pipe, ignition system, data acquisition system, high-speed image acquisition system, and gas distribution system. The length of the explosion pipe is 1000 mm, and the cross-sectional area is 50 mm × 50 mm. The plexiglass pipe wall thickness is 30 mm. The experimental condition is that the left end is closed, and the open end was covered by PVC. The ignition system consists of the pulse igniter and platinum ignition electrode. The ignition electrode was made of platinum wire with a diameter of 0.10 mm, and the ignition spacing is 2 mm. The HM-90 high-frequency pressure sensor and NI USB-6251 data acquisition card were used for pressure data acquisition. The ignition signal was captured using the RL-1 photoelectric sensor. The high-speed camera is MIRO M-310 of York Company in the United States. The shooting speed is 2000 fps. The maximum resolution is 1024 × 800, and the gas distribution system adopts the D08-1F mass flow controller and stainless-steel gas mixing premix device.

4. RESULTS AND DISCUSSION

4.1. Model Selection Judgment. The work presented in this paper used the same laminar model of premixed flame propagation described and validated by Bychkov et al. The stoichiometric methane/air with an equivalent ratio of one deflagration in a horizontal half-open pipe (25 mm radius and 1000 mm length with the ignition point at the left-center position) is simulated. Clanet and Searby analyzed the numerical model to find that the model could be used to calculate the acceleration of the flame tip, the position of the flame skirt touching the sidewalls, and the interval between the three stages of the tulip. The ignition device is centered at the closed end, and the flame propagates to the open end. Based on the theory, the time taken for the flame to spread from a spherical shape to the fingerlike front end will be proportional. When the shape of the flame turns to the finger shape:

\[ \tau_{tup} = \frac{1}{2\alpha} \]  

(6)

where \( \alpha = \sqrt{E(E - 1)} \). \( E = \rho_u/\rho_b \) is the gas expansion factor, which defines the density ratio of the fuel mixtures (\( \rho_u \)) and the burnt matter (\( \rho_b \)). As the flame spreads from the ball to the fingerlike front, the flame accelerates and stops until touching the sidewalls. When the flame skirt touches the sidewalls at the characteristic time:

\[ \tau_{wall} = \frac{1}{2\alpha} \left( \frac{E + \alpha}{E - \alpha} \right) \]  

(7)

The time of flame inversion

\[ \tau_{tup} = \tau_{wall} + \tau_{inv} \]  

(8)

where \( \tau_{inv} = \lambda/\alpha \) is the time interval of the third stage. \( \lambda \) is the coefficient comparable to unity. In addition, the theory of the simulation is based on the empirical model in the literature, so \( \lambda \) is taken as 1.

The front position of the flame is given by

\[ \xi_{tip} = \frac{E}{4\alpha} \{ \exp(2\alpha \tau) - \exp(-2\alpha \tau) \} = \frac{E}{2\alpha} \sinh(2\alpha \tau) \]  

(9)

During the acceleration phase, the front end of the flame accelerates exponentially with growth rate

\[ \theta = 2\alpha = 2\sqrt{E(E - 1)} \]  

(10)

The theory was tested by Clanet and Searby and DNS with good agreement. Note that the principle was grown for the propagation of flames in the laminar with almost constant pressure and velocity. Therefore, it could be known that the theory can be applied to the early stage of flame spread experimentally, and as the pressure changes slightly, the combustion rate is not influenced by the development instability. The analytical formulas may result in an over-estimation of flame tip velocity in the later stages of flame spreading in the closed pipe: the speed of flame propagation would slow down because the gases cannot travel freely to the closed end. However, this paper mainly studies the early stage of flame propagation, so the effect is not significant.

In Figure 3, the numerical result was compared with the experimental and theoretical ones based on the flame tip position to validate the numerical model. Owing to the similarity in the evolution of the flame shape in the tubes, which has been confirmed by the similarity of flame by dimensionless extrapolation in these studies, when comparing the axial position of the flame, it can also ensure...
the accuracy of the lateral position of the flame. The results show that the numerical results are in good agreement with them. The numerical predictions of methane/air were obtained in the computational domain with the angle $\theta = 0$ and the length $= 1000$ mm. The experimental results were attained in a self-built premix explosion experimental device, as is shown in Figure 2, where the size of it was the same as the computational domain. In the theoretical model, the potential ow was not a constant value, without considering the effect of the flame curvature. In the numerical simulation, several modified simplified reaction mechanisms proposed by Westbrook and Dryer$^{32}$ may result in a deviation between the flame thickness, Lewis number, Markstein length, and the actual value. In the experiments, the premixed gas cannot be regarded as an ideal gas, and the chamber is a square horizontal pipe. However, it has been validated$^{20,33,34}$ that the square pipe is also in good agreement with the theory. All these result in the discrepancies between the three curves here. However, the simulation can predict the propagation of the flame to some extent. Before the flame skirt touched the sidewalls, the calculated flame propagation trend was basically well matched with the experimental and theoretical ones in Figure 3.

4.2. Flame Shape Changes and Development of the Flames. Figure 4 shows an elaborate (one-to-one) comparison between the experimental and numerical results. The experimental and simulated early stages of flame developing are shown in Figure 4a,b, respectively, and the experimental and simulated later stages are shown in Figure 4c,d, respectively. In order to ensure the accuracy of the data, the experiment should be repeated four times. The results showed that the structure of the flame and the time of the four classical stages have good repeatability.

For the classical tulip flame, Clanet and Searby$^{15}$ visually recorded the flame propagation process and distinguished four typical stages: hemisphere, finger-shaped, connecting with the sidewalls, and tulip-shaped. As shown in Figure 4a and c, the premixed CH$_4$/air flame went through the classical four stages. After ignition, $0 \text{ ms} < t < 1.3 \text{ ms}$, the flame expands spherically without the impact of the sidewalls. As the flame approached the sidewalls, $1.3 \text{ ms} < t < 16.7 \text{ ms}$, the structure of it changed from hemispherical into finger shape, and in this stage, the flame surface and the flame propagation speed increased exponentially. At the third stage, $16.7 \text{ ms} < t < 26.5 \text{ ms}$, the skirt of the flame began to touch the sidewalls, resulting in the speed and the surface of the flame to decrease. Actually, it was a little difficult to find the accuracy moment of the elongated flame skirt touching the sidewalls. As shown, at $t = 26.5$ ms, a planar flame occurred, which was the beginning of the tulip flame formation with a cusp pointing backward to the burnt gas. Figure 4b,d shows the results of simulation with $\theta = 0$, and the four phases are (i) the spherical flame phase, $0 \text{ ms} < t < 1.2 \text{ ms}$; (ii) the finger flame phase, $1.2 \text{ ms} < t < 16.7 \text{ ms}$; (iii) the flame skirt connecting the sidewalls, $16.7 \text{ ms} < t < 27.4 \text{ ms}$; and (iv) the tulip flame, $27.4 \text{ ms} < t$. The tulip flame occurs after the flame front velocity slowed down sharply, and the inversion of the flame tip resulted in the increase in flame surface area, increasing the velocity of the flame front and pressure. There are many different opinions about the inversion of the flame tip; Gonzalez$^{29}$ explained that the tulip flame was the consequence of the coupling between the velocity and the generated compression wave. However, Ponizy et al.$^{17}$ thought that the “tulip” flame was just a purely hydrodynamic phenomenon, unrelated to the Rayleigh–Taylor and Richtmyer–Meshkov instabilities. In the simulation, it is investigated using the laminar model that the inner ow is regarded as the laminar ow in all stages, but the laminar flame turns to the turbulent flame after forming a tulip flame, which has been validated. Hence, there are certain discrepancies between the calculation of the tulip flame and the experimental result. Especially after the tulip flame formed, the flame skirt appeared a little bit different from the experiment. It does have discrepancies in the simulation results, but the simulation can predict the propagation of the flame to some extent. The time of the four classical stages is in good agreement with the calculated results.

Figure 5 displays a series of simulated images of premixed methane/air flame propagating in the half-open ducts, stating the development of flame shapes. For tulip flames, there are four classical structures of flame that could be witnessed: spherical flame, finger-shaped flame, flame with the skirt touching the sidewalls, and tulip flame. In this study, it mainly focuses on the inhibition of the formation of tulip flame dynamics by changing the angle of the sidewalls and promotion of the premixed flame combustion.

In the present simulation, the spherical or hemispherical stage lasts for a short time after ignition; although it is not going to change much at the beginning, it is going to get shorter as the angle $\theta$ increases. First, the flame spreads spherically without any influences on the sidewalls of the duct. Next, the flame begins to elongate horizontally from the sphere to the finger shape, as shown in Figure 5. At the finger-shaped flame stage, the surface area of the spreading flame increases exponentially, which results in the rapid acceleration of the flame tip.$^{15,28}$ With the increase in angle $\theta$, the sidewalls may hinder the spread of the front end of the flame, which would increase the speed of the flame tip even further. Moreover, the duration is shorter, which may be caused by the accelerated velocity of the flame tip. The flame acceleration terminates when the flame reaches the sidewalls. At the third stage, as the skirt of the flame touches the sidewalls, the flame stopped acceleration. Then, the decreases in flame tip velocity and the flame surface area were due to the part flame touching the sidewalls being quenched near the sidewalls. In the meantime,
the curvature radius of the flame front increases. As can be seen in Figure 5, the position where the flame developed into a flat shape was postponed as the angle \( \theta \) increased, and the time of its appearance was also postponed. The classical tulip flame is subsequently formed when angle \( \theta = 0, 0.1, \) and \( 0.2 \), but there is no fourth stage, the classic tulip flame when angle \( \theta = 0.3, 0.4, 0.5, \) and \( 0.6 \). Note that the surface of the flame grows smoothly before the inversion of the tip and then starts to wrinkle, which results from the hydrodynamic instability because the Lewis number of the premix CH\(_4\)/air is near 2.2, leading to flame diffusion stability. The flame surface area is increased by the wrinkling instability. Furthermore, the time it takes for the tulip flame to appear becomes longer, and when the tulip eventually reaches the end of the pipe, the distance from the sunken part of the flame to the front of the flame decreases as the angle \( \theta \) increases, in Figure 5. Above all, it can be found that the effect of inhibition on the formation of the tulip flame is more obvious with the increase in angle \( \theta \). Finally, when the angle \( \theta \) is bigger than one certain value, the tulip flame would disappear.

4.3. Flame-Pressure Interaction and the Velocity of the Flame. Figure 6 presents the propagation velocity, the pressure profile, and the flame surface area at various moments. Because \( \theta = 0.6 \) has the same trend as \( \theta = 0.5 \), it is omitted. Here, the pressure is measured at the monitoring point-ignition position. The flame surface area is calculated by the ratio of the fuel mass fraction to the initial fuel mass fraction. When angle \( \theta \) ranges from 0 to 0.2, there would be tulip flames. The velocity of the flame is based on the changes in the distance between the leading tip and the leftmost end with time. From Figure 6, the periodic oscillations of the flame front velocity and the initiation of the tulip flame coincided with the sudden deceleration of both the flame front and pressure growth. The flame contacts with the sidewall causing the flame surface area
to decrease dramatically, which is also the reason for the first deceleration\(^2\),\(^{15,26}\). During the development of the premixed flame, it can be found that the variation trends of the flame surface area and flame velocity are basically the same and change quantitatively with time. It has been proved that sudden deceleration of the flame occurs after the first contact with the sidewalls, resulting from the less flame surface area.\(^2\),\(^{26,27}\)

Figure 7 shows the development of the pressure at different angles. As seen in Figure 7, the maximum of the pressure increases with the increase in angle \(\theta\). When the angle \(\theta\) ranges from 0 to 0.2, the tulip flame appears. Meanwhile, it is important to find that the angle \(\theta\) is bigger than a certain angle, the pressure curve does not have two peaks, and the only peak increases as the angle \(\theta\) increases. It can be found that both sidewalls have an oppressive effect on the coming flame so that the pressure is increasing and the maximum speed also increases, as shown in Figure 6. Because the absolute flame velocity is the sum of the laminar combustion velocity of the flame and the velocity of the fresh gas, the sharp deceleration of the flame after the second stage and before the planar flame occurs, and a sharp deceleration of the flame means a significant reduction in the flow rate of the fresh gas.

The oscillation of the pressure wave is caused by the quickly decreased velocity of the third-stage flame leading tip.\(^2\),\(^{26}\) Moreover, it is easy to find that the pressure growth oscillation period is well matched with the velocity oscillation period. The front of the flame contacts the sidewalls, triggering a pressure wave that travels back and forth through the pipe. The time for the tulip flame to appear is getting postponed with the increase in angle \(\theta\). The change in angle makes the shape of the calculated area change, which will affect the superposition and counteraction between the pressure wave formed by the flame surface, and the reflected wave propagated to the wall, reflected in the velocity and structure of the flame and pressure, which turns more obvious with the increase in angle \(\theta\), especially at angle \(\theta = 0.3, 0.4, 0.5,\) and 0.6. Gonzalez\(^28\) used numerically studied methods and found that the acoustic wave has a weak effect on the flame front. After the collapse of the flame tip, the flame is driven by periodic acceleration, which gradually leads to the oscillation of the total heat release and pressure phase, resulting in violent instability. Markstein\(^29\) also found that the appearance of the tulip flame was closely related to the sudden drop in the speed of the flame front. However, in this numerical simulation, the sidewall speed changes a little, but the big change occurs in the symmetry velocity with the increase in angle \(\theta\); finally, when the angle \(\theta = 0.3, 0.4, 0.5,\) and 0.6, the symmetry velocity becomes bigger than the sidewall velocity, which makes the tulip flames to disappear. The pressure wave effect causes the velocity of the unburned gas to change dramatically with the appearance of the tulip shape, leading to a sharply fallen velocity of the unburned mixture and backward flow in the fresh region, as shown in Figure 6. In this study, the pressure wave as a source, similar to the shock wave speed of the change and deformation of the fresh zone immediately begins to flame, experienced a sudden deceleration.

The speeds were compared without a sudden deceleration when the angle \(\theta = 0.3, 0.4, 0.5,\) and 0.6, which also proves to be consistent with the abovementioned cause of tulip flames. The biggest numbers of the three flame propagation speeds are shown in Figure 8; symmetry velocity keeps increasing, but

![Figure 5. Numerical flame shape of the combustion duct at angle \(\theta = 0\) (a), 0.1 (b), 0.2 (c), 0.3 (d), 0.4 (e), 0.5 (f), and 0.6 (g). The colors designate the temperature from the fresh mixture (blue) to the burnt gas (red).](https://dx.doi.org/10.1021/acsomega.0c03667)
sidewall velocity changes more than that during the angle \( \theta = 0, 0.1, \) and 0.2. Sidewall velocity starts decelerating; in contrast, symmetry velocity still keeps increasing but so fast when the angle \( \theta = 0.3, 0.4, 0.5, \) and 0.6. At the same time, the pressure oscillations are very similar to the pressure oscillations in the early flame phase of Gonzalez numerical simulation. Hence, the reason for the disappearance of tulip flames has the same physical origin as Markstein’s experiment.\(^{29}\)

4.4. Dynamics of the Flame Front and Velocity. Figure 9 is the calculated location of the flame front at various moments. This type of flame tip position is measured as the distance from the left end of the duct. As can be seen in Figure 9, the flame position expansion rate increases with the increase in angle \( \theta \) from 0 to 0.3; however, the flame position expansion rate decreases with the increase in angle \( \theta \) from 0.4 to 0.6. The flame leading edge of the center line and the flame front of the side part are, respectively, used as the flame guide tip before and after the flame flip. Figure 6 displays numerical displacement speed, the pressure profile, and the surface area as a function of time at \( \theta = 0 \) (a), 0.1 (b), 0.2 (c), 0.3 (d), 0.4 (e), and 0.5 (f).

Figure 6. Variation of the flame surface area and the propagation velocity of the flame and overpressure as a function of time at angle \( \theta = 0 \) (a), 0.1 (b), 0.2 (c), 0.3 (d), 0.4 (e), and 0.5 (f).
reduces the flame surface area. Before the flame starts inversion, the decrease in flame surface area is due to the fact that most of the unburned mixture is consumed. Actually, in order to mitigate the loss of velocity at the flame tip, the flame surface is strongly curve-shaped to compensate for the flame surface area and causes the flame tip to be inverted. As shown in Figure 10, the time for starting to decrease the flame surface area is postponed, and the flame surface area enlarges with the increase in angle $\theta$ from 0 to 0.2. The formation of the tulip shape leads to another increase in flame surface area. As a result, the flame accelerates again after inversion. Wrinkles on the flame surface increase the flame surface area. As a result, the flame accelerates for the second time after reversing. Note that in the third stage, the flame surface area begins to decrease and reaches a minimum at the flame, which has been proved both experimentally and numerically, so as to the periodic oscillations of flame velocity. With the increase in angle $\theta$ and the angle $\theta$ being greater than 0.3, the structure of the flame propagation dynamics only experienced three stages, namely, hemisphere, fingerlike, and skirt touching the wall, without the formation of the tulip flame. It may be due to the change in wall angle, which reduces the velocity of the flame area, decreasing after touching the wall, so that the flame velocity comes out of the horizontal pipe in the first three stages. It illustrates that changing the angle between the wall and the horizontal line is conducive for promoting the speed of the front end of the flame and inhibiting the formation of the tulip flame.

Figure 11 shows the vector velocity field and vortices after ignition near the flame surface at different angles $\theta$. This also reflects the influence of different angles on the flow pattern, and the interaction between the flame and pressure wave could result in diverse flow patterns. Starting with the finger-shape flame touching the sidewalks, the fresh zone and the burned zone are primarily subjected to positive and negative flows individually. The positive flow is distributed near the tip of the lips, passing through the lips, and the negative flow traverses the front end of the flame and seams the front forward flow. Thereafter, with the increase in angle $\theta$, the positive flow fades in the vicinity of the tulip lips, and the flow direction changes, as shown in Figure 11. The positive flow still takes place in the tulip lips, but as the flames grow, they take up less space, and the flow of the flame front center even turns positive. This performance makes the distance shorter between the front and inverted cusps; evidently, the positive flow takes up the whole unburned region. Near the sidewalks, the lips of the tulip are...
controlled by the backward flow. Nevertheless, the velocity vector behind the flame surface starts at the lip of the inversion, pointing to the unburned gas and the sidewalls. This flow pattern causes the flame to quench near the sidewall and the flame area to decrease, with the increase in the angle $\theta$ from 0 to 0.2. Because there is adiabatic and no-slip boundary condition in the simulation study and there is a little friction on the flame surface during the experiment, the flame deceleration will be more obvious. After the flame inversion, in consequence of the interaction between the flame front dynamics and the compression or reflected waves, the opposite flow controlled the whole area nearby the flame front. This helps the tip to move backward, and the flame front reverses. The reverse flow passed through the flame front and joined together with the positive flow ahead of the flame front. In Figure 11a,b, in the hemispheric and fingerlike flame stages, the velocity vectors do not swirl. There are vortices in the tulip flame phase. In Figure 11c,d, the velocity vector always moves in the same flow mode, which can accelerate the flame speed without flame inversion. Overall, by comparing the four figures and changing the angle of the pipe, the flame vector flow pattern can be influenced to promote the flame and inhibit the formation of tulip.

5. CONCLUSIONS

In this paper, the propagation of methane/air flames in half-open ducts with different angles $\theta$ between the sidewall and the horizon was investigated using two-dimensional simulation. The numerical result was compared with the experimental and theoretical ones to validate the numerical model. The results show that the numerical results are in good agreement with them.

The position where the flame front begins to concave is pushed back with the increase in angle $\theta$. The so-called “tulip” flame even does not occur, if the angle $\theta$ is bigger than 0.3. What is more, for CH$_4$/air mixtures, the so-called “tulip” flame does not occur, when the angle $\theta$ is around 0.3 to 0.6. Moreover, the flame propagation speed and pressure become bigger as the angle $\theta$ increases.

1) The numerical results show that changing the angle $\theta$ between the sidewall and the horizon can effectively affect the interaction of the flame front and the generated pressure to promote the development of the methane/air flame and inhibit the formation of tulip flames.

2) Numerical simulation shows that the acceleration of the flame leading edge along the top wall is mainly caused by the hydrodynamics generated by the combustion, which results in the intense chemical reaction of the gas through the flame surface into the gas to push the flame surface to accelerate.

3) The vortex motion formed before the flame concaves is the chief factor of the cusped flame and the subsequent tulip flame. However, as the angle $\theta$ increases, the development of the flame is blocked, which results in the vortex motion being blocked. Thus, we inhibit the formation of the tulip flame to promote flame combustion.

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