

Numerical Simulation of Flow and Heat Transfer Characteristics in Biomass Feeder

Zhenhua Wang^{a,*}, Yulong Chang^b, Zheming Liu^c and Hualin Wang^d

State Environmental Protection Key Laboratory of Environmental Risk Assessment and Control on Chemical Process, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, P.R. China

*Corresponding author e-mail: wzh_ecust@126.com, ^bchangyulong1218@163.com, ^clzmzmm1711@163.com, ^dwanghu@ecust.edu.cn

Abstract. In this paper, designed a swirling feeder for biomass tar, The numerical simulation of flow characteristics and temperature field heat transfer characteristics of the internal flow field was performed. Mixture multiphase flow model and Reynolds stress turbulence model are used, in the case of different feed flow ratios, Solved the internal flow field, concentration field and temperature field; Through research shows that when the flow ratio $i = 0.6 \sim 0.8$, Biomass tar can enter the reactor through the feeder without causing coking.

1. Introduction

In the field of biomass energy, biomass pyrolysis, liquefaction and other processes to produce biomass tar (commonly known as wood tar), and then through the refining of biomass tar to produce gasoline, diesel or aviation fuel, etc., is a more efficient way of energy use [1]. However, before the biomass tar enters the reactor, due to the lack of catalyst, the high temperature of the pipeline will cause a violent polymerization reaction of the biomass tar to cause coking, resulting in equipment clogging or even damage [2]. To avoid this coking, the biomass tar can be pretreated by filtration, decarburation, etc., but the process and production costs are increased; another solution is to change the traditional way of feeding and design a feed device dedicated to biomass tar [3].

Examining many documents, it is found that there are few studies on biomass tar feeding. However, in the field of catalytic cracking, the study of heavy oil feed nozzles has been relatively mature, and there are many different types of nozzles used in industrial production [4]. The common types of nozzles include throat nozzles, target feed nozzles, bubble atomizers, and swirl atomizers [5]. These studies provide a guiding method for the design of biomass tar feeders [6]. Based on the existing process, this article designs a swirling feeder. And under different working conditions, CFD numerical simulation of the feeder, to understand the flow and heat transfer and mixing rules, to provide guidance for the development of wood tar refining process technology.



2. Control equations and numerical dispersion

2.1. Feeder structure parameters

Swirling feeder structure as Fig 1 shown. Wood tar enters the feeder from the axial inlet, and low-temperature diesel acts as a hydrogen donor, entering the feeder from the tangential inlet. Through the diversion effect of the swirl chamber, a low-temperature diesel stream is formed in close contact with the swirling motion of the inner surface of the spiral wound feeder. The wood tar is prevented from coming into direct contact with the high-temperature pipe wall and is finally sprayed into the reactor by an umbrella-like injection port.

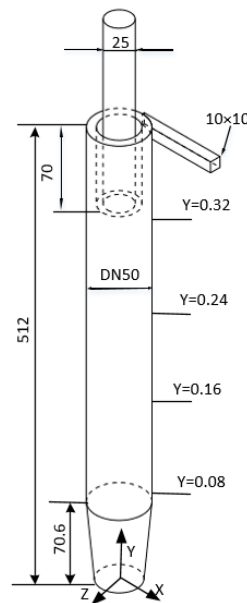


Figure 1. Feeder structure parameters

The physical parameters of wood tar and diesel are shown in the Table 1

Table 1. Physical parameters of wood tar and diesel

Name	Diesel	Wood tar
Temperature /(°C)	50.5	50.45
Molecular weight	166.8664	174.783
Cp/(KJ·kg ⁻¹ ·K ⁻¹)	0.4241	0.3839
Density /(kg·m ⁻³)	892.8197	1004.0049
Viscosity /(cp)	1.7394	1.8899

2.2. Control equation

The flow field in the feeder is a highly rotating turbulent flow field. In this paper, the Mixture model and Reynolds stress turbulence model are used, and it is assumed that the flow is constant and the time-averaged solution is obtained. Reynolds stress model RSM more strictly considers the streamline bending, eddy current, rotation and tension changes, establishes the Reynolds stress differential equation directly, and directly solves the distribution of fluid flow parameters through 7 equations, solve the non-closed problem of the dissipation rate and the Reynolds pressure equation, and have higher prediction potential for complex flows. The specific form of each equation in the Reynolds stress model is:

Continuity equation:

$$\frac{\partial(\rho U_j)}{\partial x_j} = 0 \quad (1-1)$$

Momentum equation:

$$\frac{\partial(\rho U_i U_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho \overline{u_i' u_j'} \right) \quad (1-2)$$

The model closed the basic equation by solving the following Reynolds stress transport equations:

$$\frac{\partial}{\partial t} (\rho \overline{u_i' u_j'}) + \frac{\partial}{\partial x_k} (\rho U_k \overline{u_i' u_j'}) = D_{ij} + p_{ij} + \Pi_{ij} + \varepsilon_{ij} \quad (1-3)$$

The above equation is obviously not a closed system and must be approximated by turbulent simulation so that the Reynolds stress equation is closed. After the equation is closed by simulation, the specific forms of the right-end items are as follows:

Diffusion items:

$$D_{ij} = -C_\mu \rho \frac{k}{\varepsilon} u_i' u_j' \frac{\partial}{\partial x_k} (u_i' u_j') \quad (1-4)$$

Shear force generation terms:

$$p_{ij} = -\rho \left[\overline{u_i' u_k'} \frac{\partial U_j}{\partial x_k} + \overline{u_j' u_k'} \frac{\partial U_i}{\partial x_k} \right] \quad (1-5)$$

Stress and strain items:

$$\Pi_{ij} = \Pi_{ij1} + \Pi_{ij2} \quad (1-6)$$

$$\Pi_{ij1} = -C_1 \rho \frac{\varepsilon}{k} \left(\overline{u_i' u_k'} - \frac{2}{3} \delta_{ij} k \right) \quad (1-7)$$

$$\Pi_{ij2} = -C_2 \left(P_{ij} - \frac{2}{3} \delta_{ij} G_k \right) \quad (1-8)$$

Turbulent energy consumption:

$$\varepsilon_{ij} = \frac{2}{3} \delta_{ij} \rho \varepsilon \quad (1-9)$$

Among them, $G_k = -2 \rho \overline{u_i' u_j'} \frac{\partial U_i}{\partial x_k}$, $k = \frac{1}{2} \overline{u_i' u_i'}$, its value is determined by the following transport equation:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho U_k \varepsilon)}{\partial x_k} = \frac{\partial}{\partial x_k} \left(C_\varepsilon \rho \frac{\varepsilon}{k} \overline{u_i' u_j'} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{\varepsilon}{k} (C_{\varepsilon 1} G_k - C_{\varepsilon 2} \rho \varepsilon) \quad (1-10)$$

This forms the closed system of equations for RSM, where the model constants are:

$$C_{\mu} = 0.24, C_1 = 1.8, C_2 = 0.6, C_{\varepsilon 1} = 1.44, C_{\varepsilon 2} = 1.92, C_{\varepsilon} = 0.13 \quad (1-11)$$

2.3. Mesh and boundary conditions

The mesh are all constructed using hexahedrons. The O-Grid strategy is used near the center and the grid near the side walls is encrypted. The grid number is about 2.34 million.

The feeder boundary conditions are set as follows: the tangential inlet and the axial inlet are all velocity inlets, and the flow rate and the corresponding k , ε are given according to the working conditions. The tangential inlet cold oil phase volume ratio is 1, the axial inlet cold oil volume proportion is 0, and the feeder outlet is set as outflow; the rest is a solid wall with a constant wall temperature of 500K. The slip-free avoidance condition is used and the non-equilibrium wall function is used in the turbulent boundary layer for calculation.

The ratio i of tangential inflow and axial inflow of the feeder is an important parameter affecting the flow field inside the swirling feeder and it is also a parameter that can be conveniently adjusted in industrial production. Each of these conditions is shown in Table 2.

Table 2. Parameters of ultrasonic surface rolling process

Flow ratio i	Diesel inlet velocity /(m·s ⁻¹)	Wood tar inlet velocity /(m·s ⁻¹)
0.2	1.976	2.185
0.4	3.952	2.185
0.6	5.928	2.185
0.8	7.904	2.185
1	9.880	2.185

3. Result and discussion

3.1. Flow characteristics

At different flow ratios, the flow conditions in the feeder are different. In order to investigate the influence of the flow ratio i , the axial velocity cloud diagram on the Y-Z plane is given under five conditions $i=0.2$, $i=0.4$, $i=0.6$, $i=0.8$, and $i=1$.

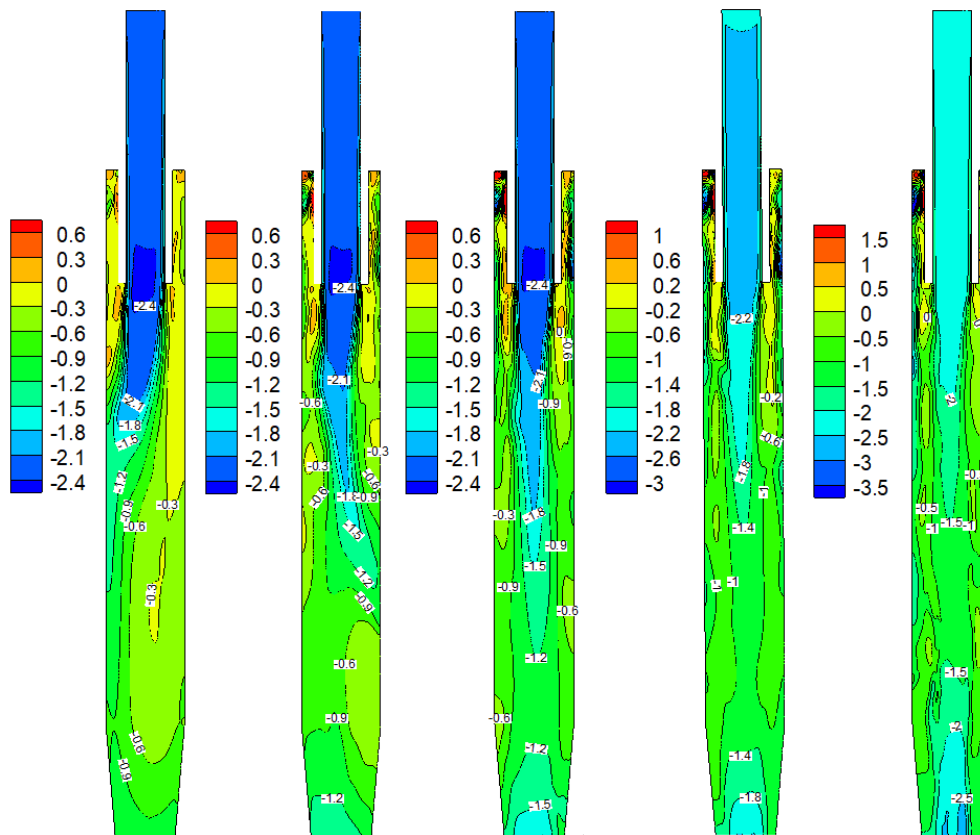


Figure 2. Axial velocity cloud diagram

As shown in Fig. 2, when $i = 0.2$ and $i = 0.4$, the flow of fluid in the feeder is deflected. Due to the low velocity of the diesel entering the tangential direction, the resulting spiral flow has a short duration. After the wood tar passes through the feeder diversion tube, it mixes with the tangentially entered diesel and flows forward together. With the increase of the flow ratio i , when $i = 0.6$, the flow in the feeder is basically symmetrical along the axis, and the middle wood tar flows faster, and the fluid on both sides makes a spiral movement along the wall. When the fluid in the feeder just enters the feeder, the velocity decreases, and finally the velocity of the fluid increases significantly when it exits the outlet.

3.2. Concentration distribution characteristics

Due to the different flow rates of the feed, the concentration distribution of wood tar and diesel in the feeder is also different. Under different feed ratio conditions, the volume fractions of wood tar and diesel on the Y-Z plane were obtained under the following five conditions: $i = 0.2$, $i = 0.4$, $i = 0.6$, $i = 0.8$, and $i = 1$.

From Fig. 3, it can be seen that under conditions where the flow ratio i is small, the wood tar and the hydrogen-donating agent are mixed in the second half of the feeder severely, and the wood tar flow is caused by the side wall and the high-temperature pipe wall. As the flow ratio i increases, when $i = 0.6$, the wood tar is substantially covered with diesel, and a diesel cushion is formed on the wall of the tube. When the flow ratio $i = 1$, due to the increase of the flow velocity, the turbulence in the feeder is serious, and the wood tar and the diesel fuel are mixed together, resulting in the thickness of the side wall cushion instead becoming smaller.

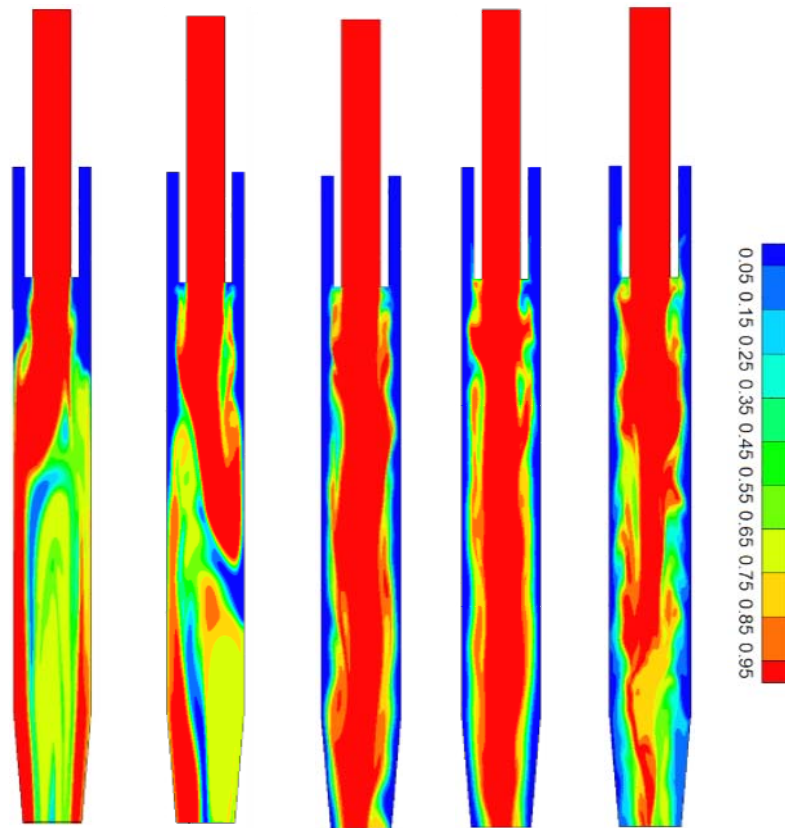


Figure 3. Wood tar volume fraction cloud

Take $Y=0.08$, $Y=0.16$, $Y=0.24$, and $Y=0.32$ to observe the volume distribution of wood tar and diesel in the feeder at different height positions. When $i=0.2$ (Fig. 4a) and $i=0.4$ (Fig. 4b), the wood tar is distributed near the axis of the feeder just after exiting the draft tube. The wood tar volume fraction at the side wall is 0, but in the second half of the feeder, the mixture of wood tar and diesel is serious and can not achieve the expected results. When $i=0.6$ (Fig. 4c), $i=0.8$ (Fig. 4d), $i=1$ (Fig. 4e), it can be found that wood tar is always distributed at the center axis of the feeder inside the entire feeder, that is, $-0.015 < Z < 0.015$. At the side wall, that is, $Z < -0.02$ and $Z > 0.02$, Wood tar has a volume fraction of almost 0. However, when $i = 1$, wood tar comes close to the feeder exit, there is a certain amount of mixing.

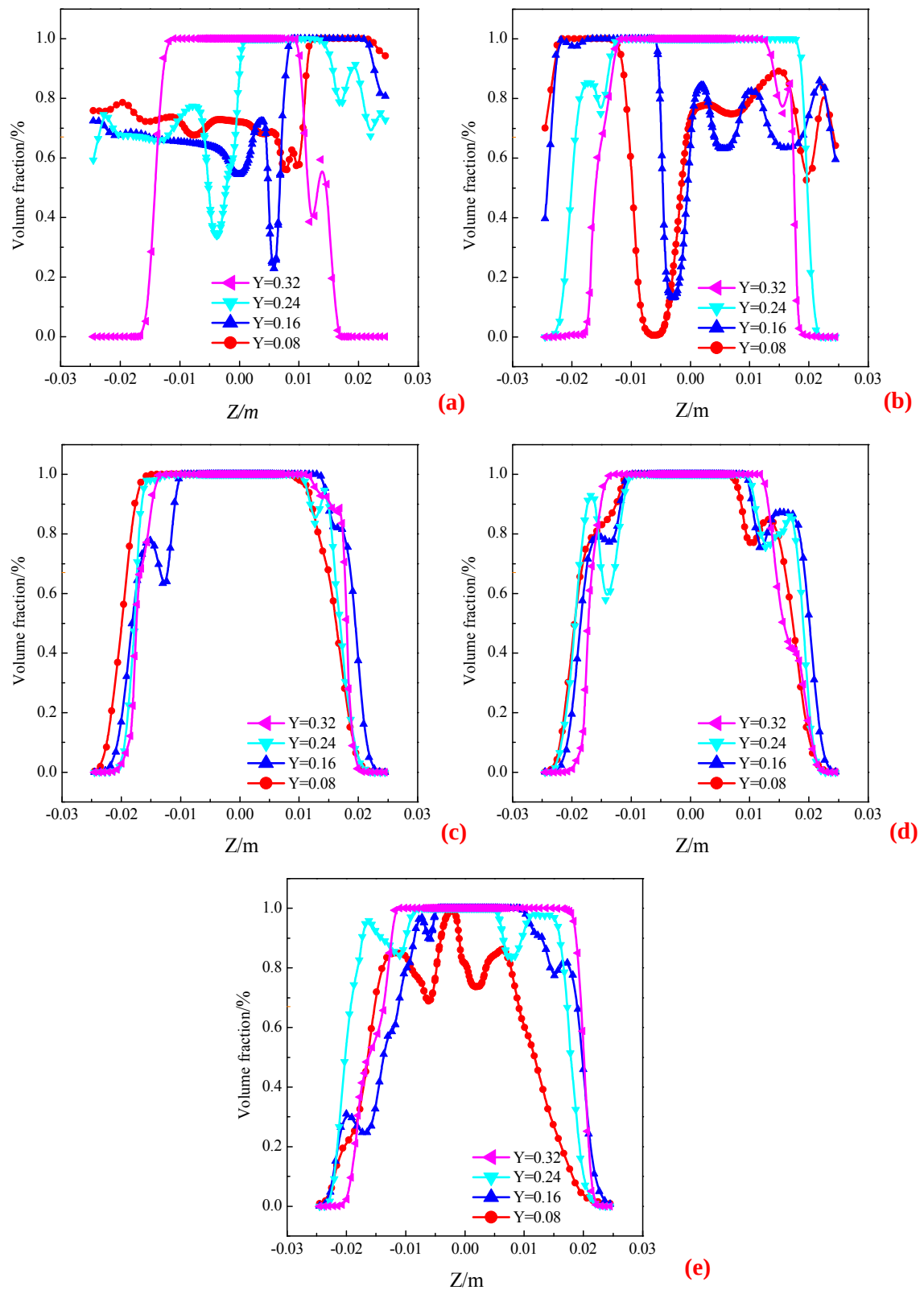


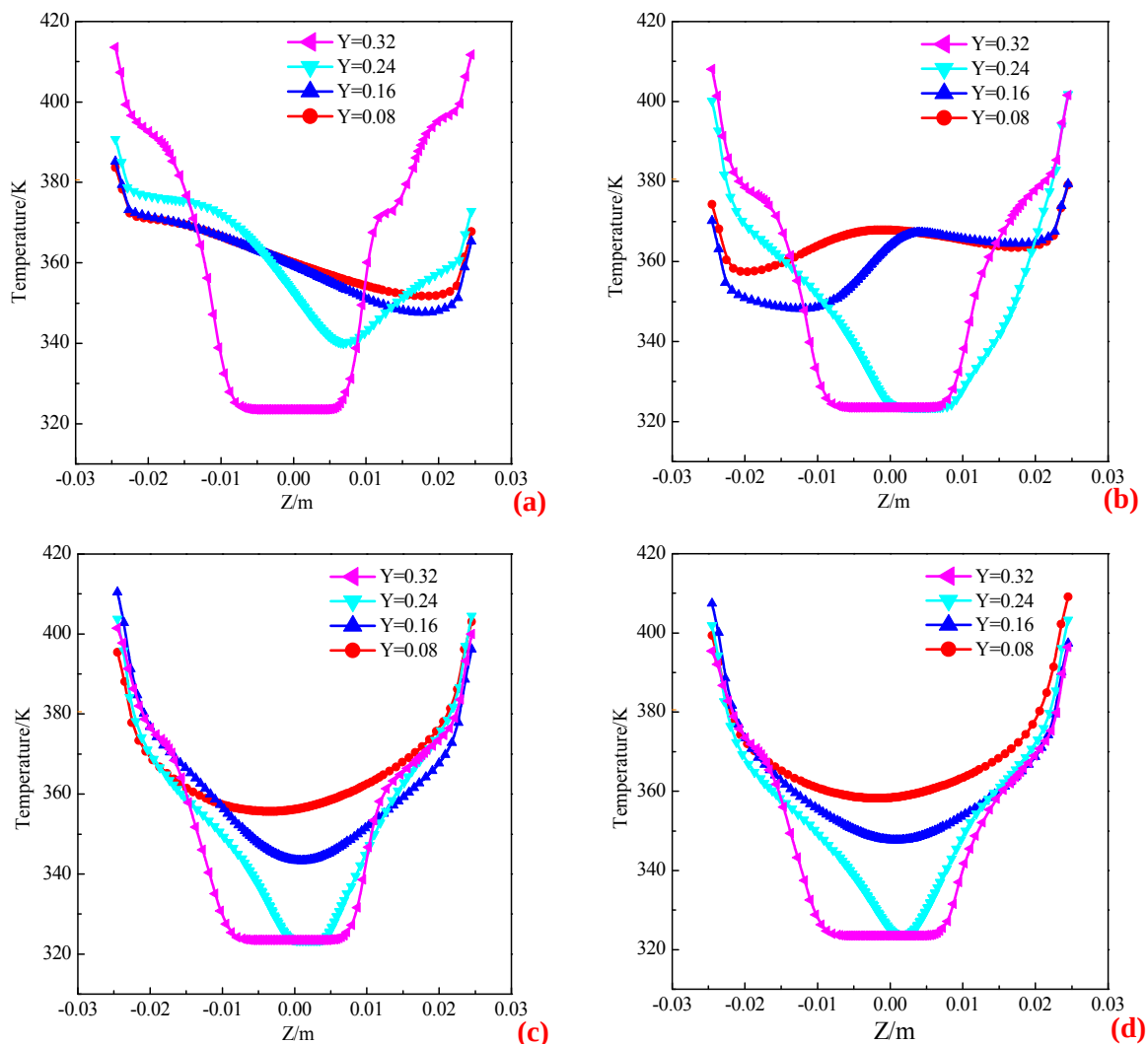
Figure 4. Wood tar volume fraction at different heights

3.3. Temperature distribution characteristics

The temperature distribution inside the feeder has an important influence on the refining of biomass tar. Take $Y=0.08$, $Y=0.16$, $Y=0.24$, and $Y=0.32$ to observe the temperature distribution at different positions of the feeder. Figure 5 shows the radial temperature distribution under five conditions.

When $i=0.2$ (Fig. 5a) and $i=0.4$ (Fig. 5b), the temperature distribution is also uneven. The overall situation is that the temperature on both sides of the wall is higher and the temperature in the center is lower. From the concentration distribution of 2.2, it can be seen that when $i=0.2$ and 0.4 , the flow of wood tar in the feeder has a biased flow, which is distributed throughout the inside of the feeder, and some of them even move to the side wall. While the temperature at the side wall can reach 400K, wood tar under this temperature condition, the coking situation is more likely to occur.

With the increase of i , the internal temperature distribution of the feeder is similar to that of the concentration distribution, and the axial distribution is symmetrical. At the heart axis, the temperature is lower, and the temperature is higher at both sides of the wall. The closer to the outlet of the feeder, the higher the temperature, which is due to the fact that after the fluid enters the feeder, the temperature of the fluid rises due to the thermal conduction of the walls. From 2.2, it can be seen that wood tar is basically distributed at the position of $-0.015 < Z < 0.015$. When $i=0.6$, the temperature of wood tar in the feeder is less than 360K. When $i = 0.8$ and $i = 1$, near the exit location, the temperature of wood tar exceeds 360K at around 370K.



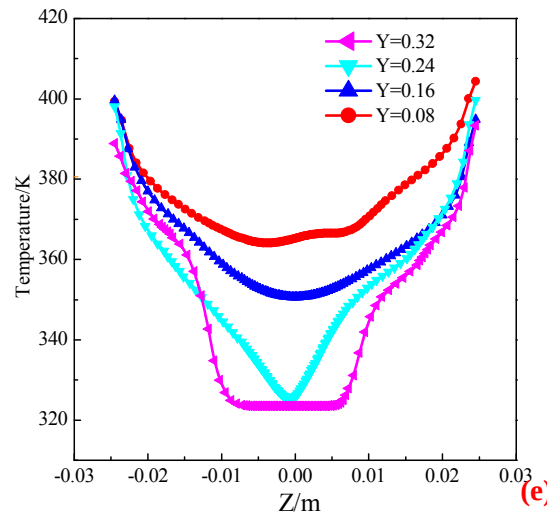


Figure 5. Temperature distribution characteristics

3.4. Concentration distribution characteristics

After entering the feeder, wood tar and diesel flow from the outlet of the feeder and finally into the interior of the reactor. Under conditions of different feed ratios, examine the speed and temperature of the outlet. As shown in Fig. 6, at the outlet of the feeder, as the flow ratio increases, both the average outlet speed and the outlet average temperature increase. Under the existing working conditions, the average outlet temperature is below 380K, and the risk of coking is small. However, in actual production, the flow ratio i cannot be too large. Otherwise, the outlet temperature is too high, which can cause coking of the wood tar.

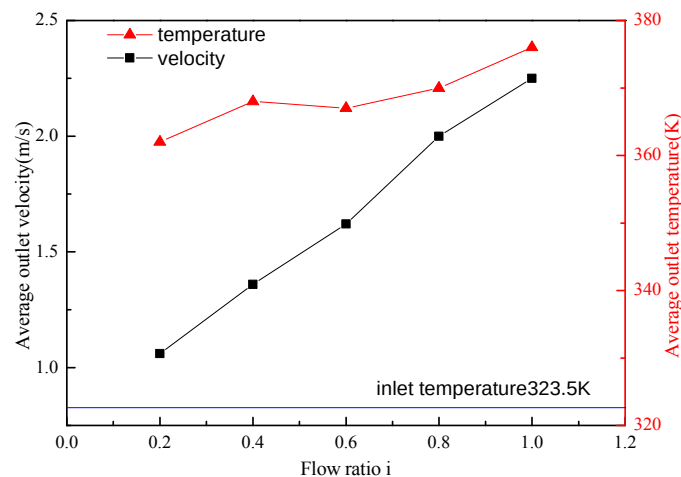


Figure 6. The average temperature and speed of the outlet

4. Conclusion and OUTlook

The conclusions obtained from this study are as follows:

(1) Under different conditions, CFD simulations were performed on the flow of wood tar and diesel oil in the feeder. It was found that the flow ratio i has an important influence on the feeder speed distribution, concentration distribution, and temperature distribution.

(2) When $i=0.2$ and $i=0.4$, the wood tar and diesel have a more serious mixture in the feeder. From the velocity field, the internal flow of the feeder has a biased flow. From the concentration and

temperature distribution, it can be known that the wood tar and the diesel fuel are mixed together, and the wood tar is distributed throughout the feeder and a part of the tar is moved to the side wall of the feeder. The temperature at the side wall is high and the risk of coking is prone to occur.

(3) When $i = 0.6$, $i = 0.8$, and $i = 1$, the feeder plays a very good role in the cushioning. The flow of wood tar and diesel in the feeder is axisymmetrically distributed. The wood tar flows along the guide pipe toward the central axis of the feeder, and the diesel makes a spiral movement along the side wall. At a position of $-0.015 < Z < 0.015$, the wood tar volume fraction is 1 and the edge wall is 0. The temperature distribution is basically similar to the concentration distribution, and the temperature of the wood tar at the center axis is lower and the side wall is higher.

(4) For the wood tar refinery, the flow ratio i should be at least 0.6 when feeding through the feeder. Otherwise, the flow is not uniform and it easily causes coking of wood tar. However, the flow ratio should not be too large. When the flow ratio $i=1$, the degree of flow turbulence in the feeder is large, and the average temperature at the outlet is also high. Therefore, it is most appropriate to take $i=0.6\sim0.8$.

References

- [1] Bauen A, Berndes G, Junginger H M, et al. Bioenergy: a sustainable and reliable energy source : main report [J]. International Energy Agency Bioenergy, 2012
- [2] Jones S B, Male J L. Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: 2011 State of Technology and Projections to 2017 [J]. Technical Report, 2012
- [3] Jones S B, Meyer P A, Snowden-Swan L J, et al. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-oil Pathway [J]. Technical Report, 2013.
- [4] G.I. Taylor, Hulka J R, Moser M D, et al. Effect of Chamber Backpressure on Swirl Injector Fluid Mechanics [J]. Journal of Propulsion & Power, 2009, 25 (4): 902-913.
- [5] Weber C, Soteriou M C. Time-resolved proper orthogonal decomposition of liquid jet dynamics [J]. Physics of Fluids, 2009, 21 (11): 112104-112104-15.
- [6] Moon S, Abo-Serie E, Bae C. Air flow and pressure inside a pressure-swirl spray and their effects on spray development [J]. Experimental Thermal & Fluid Science, 2009, 33 (2): 222-231.