Research on the features of gasoline mixture flow field with rotary jet mixing

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Abstract

Numerical simulation of the gasoline flow features and mixing efficiency in a gasoline mixture tank with a rotary jet mixing (RJM) system installed at the bottom center has been studied applying the standard turbulent model and slipping grid technique. The result shows that the RJM does well at mixing various components with no blind corner and high mixing efficiency. The mixing density difference met the mixing requirement for the first time at 31.2s and then showed a tendency of deterioration. It met the requirement again at 58.2s with the mixing density difference keeping in the mixing criterion of 3‰.

Keywords: Gasoline mixing; Rotary jet mixing; CFD simulation; Mixing quality

Introduction

Refinery enterprises usually adopt different processing technology to attain sorts of gasoline with different densities through various steps like atmospheric distillation, hydrogenation and etc. In order to meet the national petroleum products standards, the various line components should be mixed to make the gasoline physical and chemical properties more uniform. Thereby, gasoline mixing is a necessary step in the production of petroleum, the mixing efficiency directly corresponds to the quality of petroleum [1].

Gasoline mixing in refinery enterprises consists two main categories: tank mixing and pipe mixing. Tank mixing approaches include compressed air mixing [2], mechanical agitation [3]-[4] and nozzle mixing with pump circulation [6]-[8]. The first usually leads to the gasoline oxidation because of the air in the tank. Moreover, the compressed air will produce strong vortex which probably cause static electricity and this immensely threatens the tank safety. Therefore, the compressed air method has a tremendous limitation in production. Mechanical agitation is also a common method in gasoline mixing, but no matter the axial flow or the radial flow is adopted, it still causes blind corners easily which will lower the stirring efficiency with high energy consuming. High-speed nozzle jet mixing with pump circulation works in this way: the gasoline enters the tank again through the nozzle jet and the submerged jet flow will promote the motion of the static fluid, then a plenty of vortexes will generate in the boundary of jet flow, which in turn trap surrounding fluids into the jet to improve the mixing of fluids. Nozzle mixing with pump circulation is applied wider gradually for its simple structure, high safety, convenient operation and etc.

Date up to 1951, Fosset [9] had already conducted the study on jet mixing and found that nozzle mixing has higher mixing efficiency than traditional mechanical agitation; In 1982, Maruyama, Ban and Mizushina [10] found that the mixing time was up to the depth of fluid and nozzle length; In 1983, Zhu and Chang [11] introduced the principle and effect of nozzle mixing with pump circulation; In 2004, Yu [2] analyzed the features of fluid filed in a tank with a rotary nozzle and the result showed that the distribution of nozzles had an obvious effect on the fluid filed. With the development of CFD, jet stirring gets a further promotion [12]-[14]. Wang [15] studied the performance of large flux nozzle based on CFD; In 2007, Wang [16] simulated the inner flow features of jet agitator numerically; In 2012, Zhang [17] et al researched the rotary nozzle for gasoline mixing. Barekatain, H [18] et al improved the mixing by submerged rotary jet system with CFD software in a large storage tank; Neyestanak [19] et al introduced a new relation of estimating the mixing time of crude oil tank with a submerged rotary jet mixer. Zhong [20] et al studied the gas-liquid two phase flow in a slurry pool with rotary jet mixing. In this paper, CFD is used for studying the flow features and mixing efficiency in a gasoline mixing tank with RJM system.

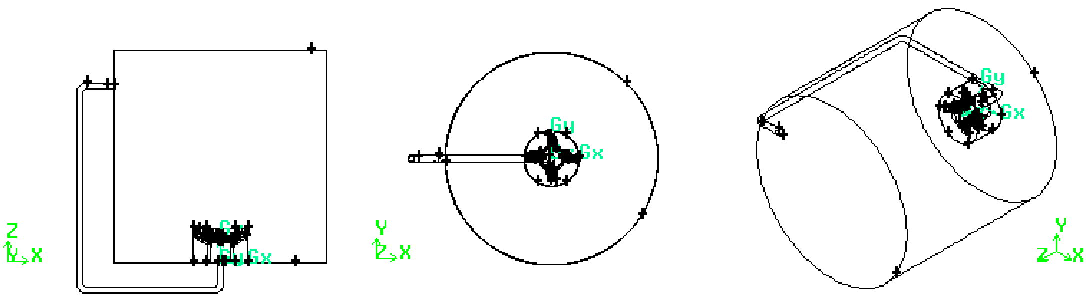

Figure 1. Sketch of the mixing tank model

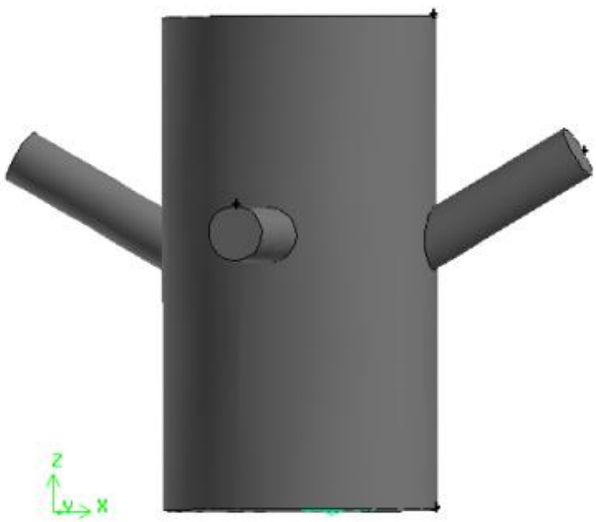

Figure 2. The RJM system with 30 °inclined nozzle

1. The geometric model and meshing

1.1 The geometric model

The geometry structure of the mixing tank is illustrated as Figure 1. Under an assumption of no pipe leak and loss of flow, the system can be assumed as closed. Thus, there does not exist inlet and outlet boundary conditions. The motivation of the whole in-tank system is provided by the source term nearby the outlet pipe, which approximates the function of circulating pump. For the convenience of calculation, the diameter and the height of the tank is set to be 1m and 2m, respectively. The diameter of the rotary jet nozzle is 26mm, of which the nozzle number is 4 in a uniform distribution across the 360 °circumferential directions. One group is horizontal and another inclined upward, of which the axis is 30 °to horizontal level. The detailed structure is showed as Figure 2.

1.2 Meshing and boundary conditions

Software Gambit 6.3 is used to mesh the model. Because the RJM system has a fixed rotating speed with constant magnitude and direction, sliding mesh is adopted to divide the whole flow zone into four parts: moving zone, static zone, source zone and pipe zone except source term. In the model, the pipe diameter is 0.03m and the interface between zones is defined as interface and the wall of RJM system is moving wall with a rotary speed of 0 rad/s relative to the moving zone showing in Figure 3. These four zones are all meshed with Tet/Hybrid 3D element. In order to assure the grid quality, the grid sizes are: 0.0125mm in moving zone, 0.02mm in static zone, 0.01mm in both source zone and pipe zone, respectively. Verified the grid independence, the total number of grids is 732205.

The operating pressure, whose value is standard atmospheric pressure 101325 Pa, is set to act on the top plane of the tank with z=1m. Gravity term with a magnitude of 9.8 m/s^2 and a direction pointing to minus z axis is chosen. Since the mixing flow field is turbulent, the standard $k-\varepsilon$ model is applied. As for the phase, four components, which can reflect the mixing state of a certain kind of gasoline, are chosen as Table 1.

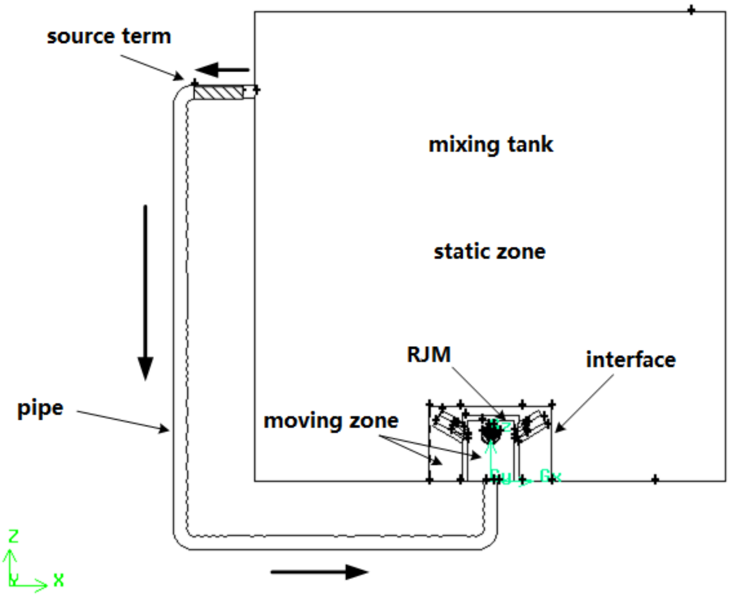

Figure 3. Divided zones in the tank

Table 1. The physical property and distribution zones of the main components of a certain brand mixing gasoline

Name	Density (kg/m³)	Viscosity (Pa s)	Z direction distribution zones(m)	Phase number
Reforming gasoline	860.7	0.00040	0-0.225+source term zone	first
MTBE	741.3	0.00036	0.225-0.315	second
Catalytic gasoline	733.2	0.00035	0.315-0.912+pipe zone	third
Gasoline alkylate	699.3	0.00034	0.912-1.0	fourth

Note: The density and viscosity of the kinds of gasoline listed above all was measured at 20℃.

1.3 Calculation strategy

The continuum equation, turbulent equation and slipping velocity equation in constant flow are solved then the volume distribution function is calculated in unsteady flow state. Therefore, the convergence can be accelerated and a convergent density field can be attained.

According to GB/T 4756-1998 manual sampling of gasoline liquid, three points, A (0.3, 0, 0.1), B (0.3, 0, 0.5), C (0.3, 0, 0.9), are chosen as density monitoring points in the mixing tank. More serious mixing time criterion is put forward:

$$t_{95\%} = \text{time for } \left|\frac{d-\bar{d}}{\bar{d}}\right| \leq 0.003 \quad (1)$$

Where d is the density of monitoring points with mean value of the whole flow field. It can be regarded as uniform mixing when the relative density value between the point A, B and C equidistant in vertical direction becomes smaller than 3‰.

2. Results and discussion

Figure 4 shows the axial velocity distribution of the RJM, in which the axial velocity in zone [-0.5, 0.5] is exactly caused by the fluid in the inlet pipe and this conforms to the velocity distribution law in pipe flow. The area nearby the wall of RJM has a minus value of velocity and this is caused by the fluid turning around after crashing the top plane of the RJM system.

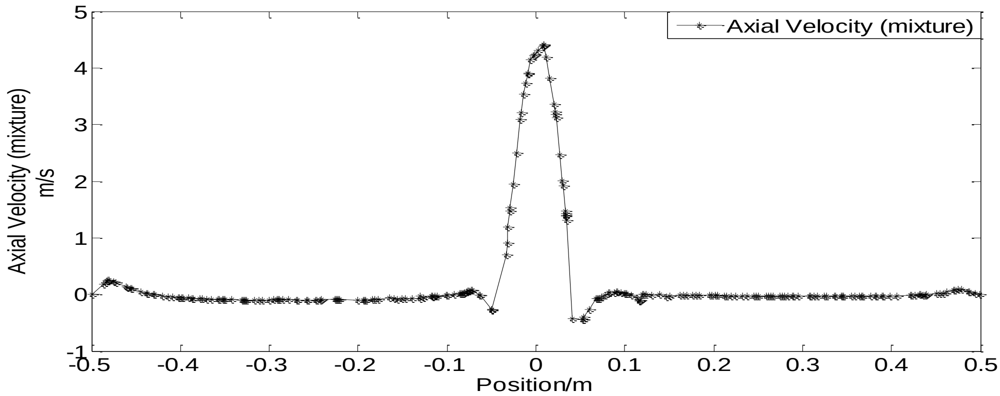

Figure 4. The axial speed distribution of the horizontal nozzles in x=0 plane

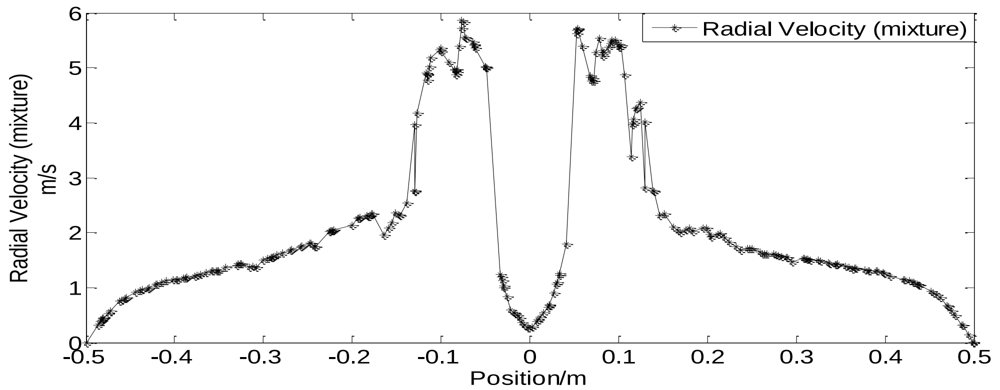

Figure 5. The radial speed distribution of the horizontal nozzles

From Figure 5, an obvious acceleration function of the nozzle can be seen. In the plane of x=0, two nozzles almost distribute equal flow flux, which thus produces the approximately same outlet velocity. Because of the interface of the moving zone and the static zone, the velocity at y=±0.13 decreases suddenly and then the velocity declines to 0.35 m/s nearby the wall gradually, which conforms to the velocity attenuation law. One inclined nozzle group distributes flow flux and velocity according to the analogous law in the y=0 plane.

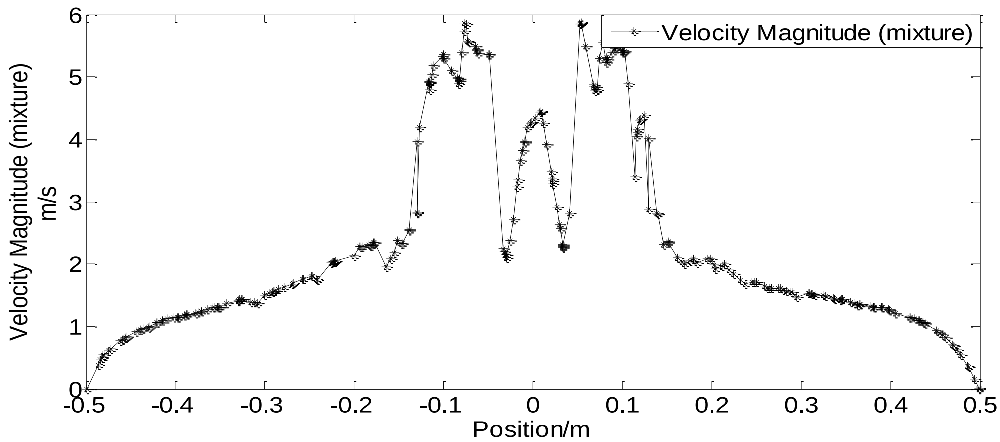

Figure 6. The absolute speed distribution of the horizontal nozzles

In the RJM system, the axial flow and circumferential flow with an order of magnitude of dominate and the radial velocity only appears at the surrounding of the nozzle inlet. The absolute velocity is obtained by combining the three velocities. As illustrated in Figure 6, a minimum velocity of 0.3 m/s can be kept near the wall of the tank, which rightly meets the requirement of gasoline mixing. Across the interface, the velocity decreases about $2/3$, and this is a factor that cannot be ignored in the numerical simulation and that is why the outlet speed needs to be larger than the theoretical calculation values.

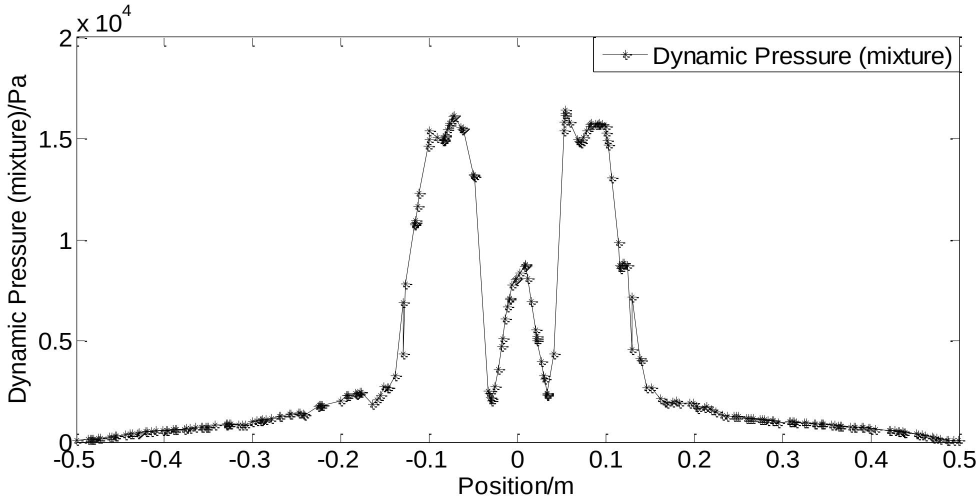

Figure 7. The dynamic pressure distribution of the horizontal nozzles

Figure 7 is quite similar to the absolute velocity distribution in their tendencies and what is different is that the effect of interface on dynamic pressure is more obvious than that on velocity. The dynamic pressure in [-0.05, 0.05] zone is mainly generated by the axial speed of the RJM while the dynamic pressure in other zones is a result of the jet speed of two horizontal nozzles, which justly verified the function of gathering energy and improving pressure of the nozzle.

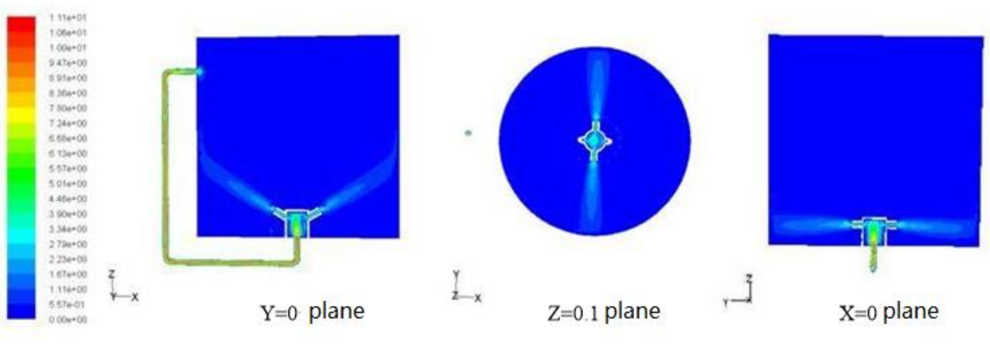

Figure 8. The velocity distribution of the mixing phase in three planes

Figure 8 is the cloud chart of speed attenuation of the horizontal nozzle in x=0 plane and of the inclined nozzle in y=0 plane. The outlet speed of the nozzle is about 5.5 m/s and the speed declined to 0.5 m/s at the wall, which is slightly larger than the required value. Thus, the source term need to be decreased. In Figure 9, the cloud chart of velocity in x=0 plane also showed the effect of gravity on jet speed and the gravity can make the jet trajectory incline to the bottom of the tank. The speed in the pipe declined slightly and the axial speed declined from 10.5 m/s at the outlet of the source term to 10 m/s at the inlet of the agitator.

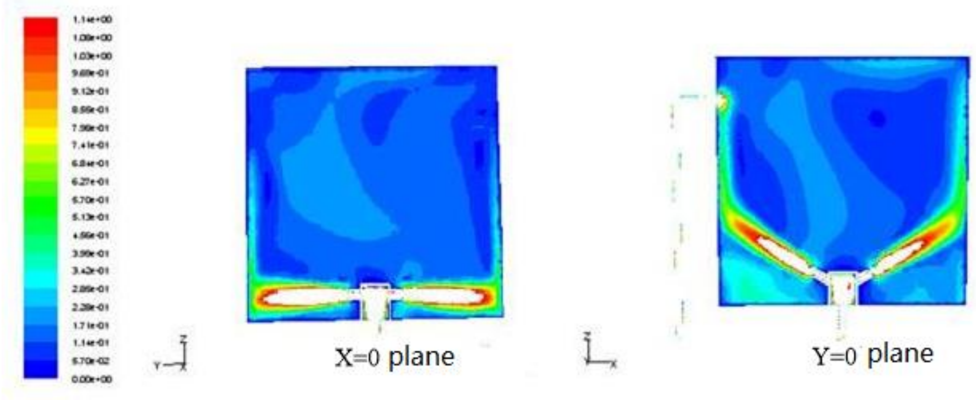

Figure 9. The cloud chart of velocity distribution in two planes

The whole flow field seems to be ideal, but there exists two low-speed zones with narrow regions in the opposition of the outlet pipe and around the RJM system. However, the so-called low-speed zones will disappear with the continuous velocity superposition with the rotation of the RJM system.

In the simulation process, besides the A, B, C monitoring points, plane z=0.1, z=0.5 and z=0.9 are monitored as well. After launching the RJM system, the third phase and the fourth phase began to enter the agitator through the pipe under the action of outlet pipe and the source term. Then these two phases jet into the first phase zone through the nozzle. Before these two phases entered the pipe, they mixed in a certain region in virtue of the speed change. Therefore, among the three planes, the density change firstly appeared in z=0.9 plane and mixing started in the other two planes in 4.4s. From the point of phase, the third and fourth phase mixed in a certain region before entering in the pipe. But in the initial time, the main mixing still happens between the main phase and the third phase with the maximum volume fraction. Finally, the density of the mixing phase approached the equilibrium density 764.5 kg/m^3.

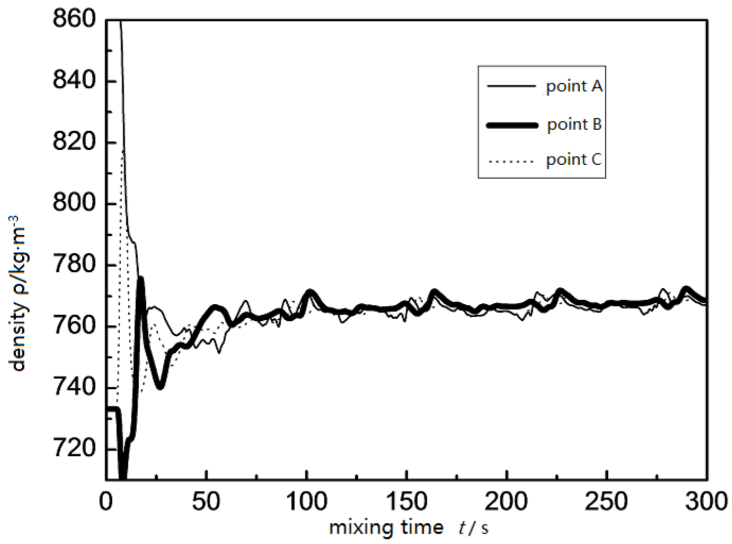

Figure 10. The density-mixing time curves of the three points

In Figure 10, the time of meeting the mixing criterion Formula 1 for the first time is at 72.4s and this is when the density of A, B C is 764.21057 kg/m ³, 763.54425 kg/m ³, 762.06708 kg/m ³, respectively. The density difference of the three is 2.81‰ and soon exceeded the limit within 1%, which is mainly caused by the sensitivity of points to value in 3D space. Hence, the mean density distribution in the three planes need to be checked.

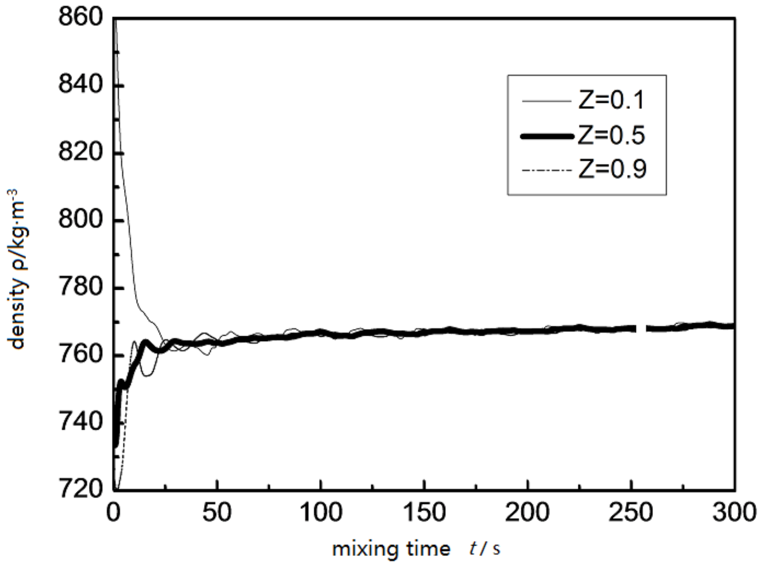

Figure 11. The density-mixing time curves of the three planes

In Figure 11, the density values in the three planes is obtained by averaging the density of all points in z=0.1, z=0.5 and z=0.9 planes respectively, which could eliminate the sensitivity of points to the result errors and could actually reflect the mixing effect of the flow field better.

The mean density value of z=0.1 plane is 761.6552 kg/m ³at 31.2s and z=0.5 is 763.9341 kg/m ³ and z=0.9 is 762.173 kg/m³. The density difference is 2.992‰. And this is the time which met the mixing criterion for the first time. But after 38.8s, it went up and exceeded 3‰. The difference decreased to 2.923‰ (Table 2) again at 58.2s and then kept within 3‰. Therefore, the mixing time of the model could be recognized to be 58.2s.

Table 2. The mean value of density in three planes at 58.2s

Z=0.1 plane (kg/m ³)	Z=0.5 plane (kg/m ³)	Z=0.9 plane (kg/m ³)	Density difference (‰)
766.4078	764.1741	764.4686	2.923

3. Conclusion

The paper analyzed the flow field features of the RJM system agitating in a tank with two 30 ° inclined nozzles and two horizontal nozzles by numerical simulation and three conclusions came to as:

a) A minimum speed of about 0.3m/s nearby the wall of the tank can meet the gasoline mixing requirements.

b) The whole flow field seems to be ideal, but there exists two low-speed zones with narrow regions in the opposition of the outlet pipe and around the RJM system. However, the so-called low-speed zones disappear with the continuous velocity superposition with the rotation of the RJM system. There is no blind corner in the agitation.
c) By analyzing the monitoring planes, it can be concluded that the mixing time of the RJM system is 58.2s and the mixing efficiency is higher than traditional methods.

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