Numerical Simulation Analysis of Oblique Impinging Jet Flow Field of Different Nozzle Structure

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Abstract Fluid jet polishing is a new precision optical machining method. The application of multiple nozzle structure and rectangular nozzle structure can effectively improve the polishing efficiency. Impact angle affects the hydrodynamic characteristics of impingement, which has an important influence on material removal and polishing effect. Therefore it is necessary to further analyze the flow field distribution characteristics of different nozzle structures with different impact angles. The circular single nozzle jet model, multi-nozzle and rectangular nozzle jet model with different impact angles are built. Based on the fluid mechanics theory, the oblique impingement process of different nozzle structure jets is numerical simulated by FLUENT, and the fluid jet velocity and pressure distribution curves on the workpiece wall have been obtained.

Key words optical fabrication; fluid jet; nozzle structure; impact angle; flow field distribution

OCIS codes 220.4610; 240.5450; 220.4880

不同喷嘴结构斜冲击射流流场数值仿真分析

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摘要 射流抛光技术是一种新型精密加工方法，多喷嘴射流结构和长条形喷嘴结构的应用可以有效地提高射流抛光效率。冲击角度会影响冲击射流的流体动力特征，对抛光材料的去除量和抛光效果有重要的影响。构建了圆形单喷嘴、三角形阵列排布及直线型排布的三喷嘴、长条形喷嘴不同冲击角度的冲击射流模型，基于流体力学，通过 FLUENT 软件对不同喷嘴结构斜冲击射流的冲击过程进行数值模拟，得到了不同冲击过程的连续流场在工件壁面上的压力、速度分布。通过比较不同喷嘴结构不同冲击角度的数值计算结果，分析了冲击角度对不同喷嘴结构流场的影响。

关键词 光学制造；射流；喷嘴结构；冲击角度；流场分布

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1 Introduction

With the rapid development of communications, aerospace and optoelectronics industry, the demand for high-precision and ultra-smooth surface components is increasing[1-2]. Fluid jet polishing is an effective ultra-smooth surface processing technology. It can be targeted to remove high-frequency surface defects. Fluid jet polishing (FJP) was first developed by Fahnle et al.[3-4] in 1998, and ultra-smooth surface with roughness of less than 1 nm was achieved, which shows that the jet polishing technology applied in precision optical processing is feasible. The jet drive the abrasive particles to impinge onto the workpiece at

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a high speed, the material is removed by the repeated collision and cutting actions in the process[5]. Removal efficiency is closely related to the pressure and the velocity distribution of flow field, therefore, the analysis of flow field characteristics is of great significance. FJP is a high precision machining method. However, the processing efficiency of a single nozzle is low, which largely limited the scope of application of FJP. Rectangular nozzle and multi-jet nozzle jets can increase the jet erosion area so as to greatly improve the efficiency of jet polishing[6]. But in the current study, jet research mainly focused on the circular single nozzle jet. There is few research on the rectangular nozzle and multi-nozzle structure jets, especially on oblique impingement jets. Research on oblique impingement jet of special nozzle structure is less. Impact angle will affect the hydrodynamic characteristics of impingement jets, in order to obtain appropriate removal effect, it is firstly need to study the flow characteristics of different nozzle structure under different impact angles as needed.

2 Basic theory

2.1 Circular single nozzle jet

As shown in Fig. 1, the flow jet ejects from the nozzle and undergoes considerable deflection after impinging on the wall surface and finally becomes parallel to the wall. For a circular single nozzle vertical impingement model, the flow field distribution is center of symmetrical. With reference to Fig. 2, when the jet impact on the wall with an angle less than 90°, the distribution of the fluid nozzle become asymmetric. Three reasonably regions of flow could be recognized [7]. Region I is referred to as the "free jet region", region II is known as the "impingement region", and it is appropriate to refer to region III as the "wall jet region". The key parameters include: nozzle diameter d, the impingement height H, the initial velocity u_0, and the impact angles θ.

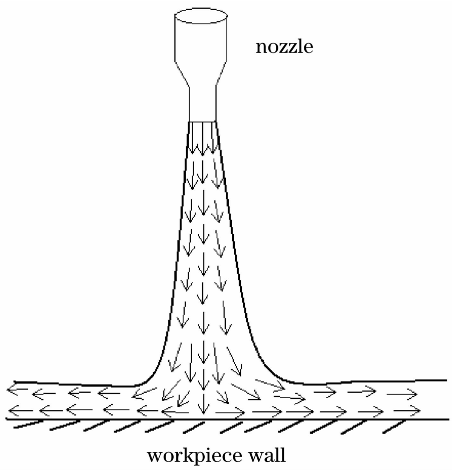

Fig. 1 Flow field of circular nozzle model

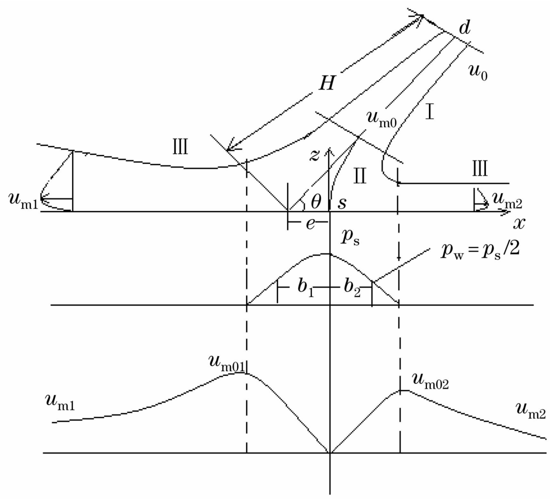

Fig. 2 Flow field of oblique impinging jet

In region I, the flow characteristics are, for all practical purposes, identical to those of a free jet. In region II, the pressure on the impingement point can be described as[8]:

$$p_s = \frac{1}{2}\rho(u_{m0}\sin\theta)^2 = \frac{1}{2}\rho\left(\frac{2.4}{\sqrt{\frac{0.86H}{d} - 2.5}}u_0\right)^2 \sin^2\theta, \tag{1}$$

where u_{m0} is the axial velocity at the end of region I. The pressure distribution on x axis in the impingement region is predicted as follows [9]:

$$\frac{p_w}{p_s} = \exp\left[-0.693\left(\frac{x}{b_0}\right)^2\right], \tag{2}$$

where $b_{0.5}$ is equal to the value of x at which $p_w=1/2p_s$ for vertical impinging jet. For oblique impinging jet, the value of x at which $p_w=1/2p_s$ on the tow sides of the nozzle are b_1 and b_2,

$$b_0=\begin{cases}b_1, x<0\\ b_2, x>0\end{cases}. \tag{3}$$

In the impingement region, in the direction from the center point outward, the value of velocity gradually increases while the pressure value decreases. When $P_w=0$, the maximum value on wall in the x direction is obtained. The maximum velocity value on the side of $\theta<90°$[8]:

$$u_{m02}=\frac{5.76}{\frac{0.86H}{d}-2.5}u_0\sin\theta. \tag{4}$$

The maximum velocity value on the other side is[8]:

$$u_{m01}=\sqrt{\frac{2\cos\theta\cdot u_0^2+(1-\cos\theta)u_{m02}^2}{(1+\cos\theta)}}. \tag{5}$$

In wall jet region, $P_w=0$, velocity value gradually reduced to 0.

2.2 Rectangular nozzle jet

With reference to Fig. 3, the velocity distribution of each point on the y axis, in x-z cross section direction, are of the similarities. Velocity distribution on the different sections can be described by the velocity distribution on the x-z plane surface. And the velocity distribution of rectangular nozzle jet on the x axis is similar with that of circular nozzle, flow field distribution on the x axis expressed by equations (1)~(4).

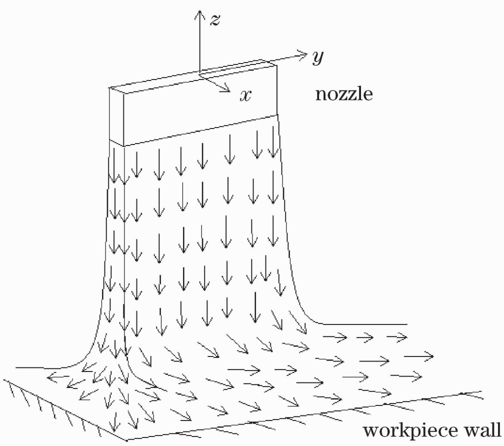

Fig. 3 Flow field of rectangular nozzle model

3 Modeling

3.1 Modeling test

Numerical simulation is an important mean to analyze the flow field. A numerical simulation software FLUENT was used, the flow is turbulent flow ($R_e>2000$) [8]. This article uses the RNG k-epsilon model to simulate the impingement process. To test the veracity and reliability of simulation method and results, the experimental result of related literature and the simulation calculated result were compared. As shown in fig. 4, the experimental curve was got by Booij et al. [10]. The slurry is guided through a circular nozzle with a diameter of 0.84 mm under an angle with respect to the surface normal of 40° and guided onto a piece of BK7. Theoretical curve was calculated by formula (5) by quoting simulation pressure and velocity distribution parameters under the corresponding condition. The simulation calculated curve is very close to the experimental curve, which verified the reliability of the simulation method.

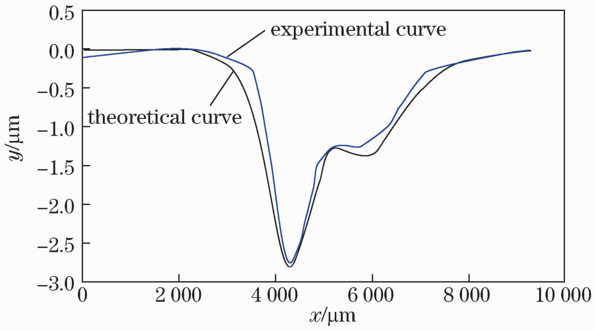

Fig. 4　Comparison between polishing profile and model profile

The RNG k-epsilon model modified turbulent viscosity, considered the rotation in the average flow and vortex flow, thus RNG k-epsilon model can better deal with high strain rate and degree of streamline curvature larger flow [11]. Calculation using the finite volume method and discrete differential equations, second order wind format is adopted to establish the discrete equations, using a SIMPLE calculation method to calculate.

3.2　Establishment of the models

Circular single nozzle models with different impact angles of 90°, 60°, 45° and 30° were established; Triangle queue arranged three-nozzle models, linear arranged three-nozzle models and rectangular nozzle models with impact angles of 45°and 90° were established too.

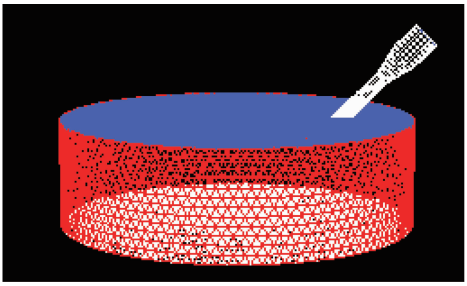

Fig. 5　Single nozzle model

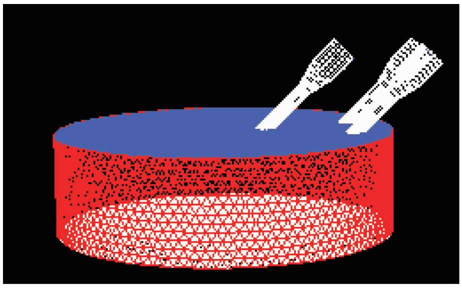

Fig. 6　Triangle arranged three-nozzle mode

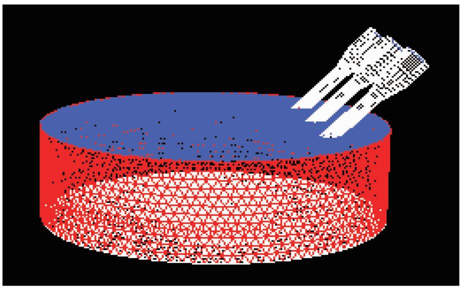

Fig. 7　Linear arranged three-nozzle model

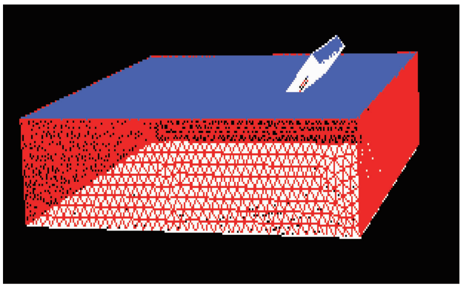

Fig. 8　Linear arranged three-nozzle model

Circular single nozzle and multi-nozzle models uses columned nozzle of d=1 mm [8]. Rectangular nozzle model has the size of 1 mm ×5 mm. The models take nozzle's impingement height as 10 mm. These impinging models with different impact angles are simulated, the pressure and velocity distributing of different nozzle structure models are gained.

4　Results and Discussion

Figure 9 are wall pressure and velocity distribution contours of vertical single nozzle model. Pressure distribution on the wall is a Gaussian distribution, velocity gets the maximum value on the ring pressure value reduced to 0.

Figure 10 shows wall pressure and velocity distribution contours of single nozzle model under the impact angle of

45°. Figure 11 shows the wall pressure and velocity distribution curve on the x axis with different impact angles of 90°, 60°, 45°and 30°. For a circular single nozzle vertical impingement model, the flow field distribution is center of symmetrical. when the jet impact on the wall with an angle less than 90°, the distribution of the fluid nozzle become asymmetric.

As the impact angle decreases, fluid begins to show an asymmetric distribution. Impact point offset to one side, the pressure and the upstream velocity (velocity on the side of impact angle less than 90°) decreases, while the change of the downstream velocity value (velocity on the other side) is small. When the impact angle is smaller than 30°, almost there was hardly any backward flow in upstream. When impact angle continues to reduce to zero, impingement jet converted to adherent jet, the maximum velocity on the wall equals the jet initial velocity.

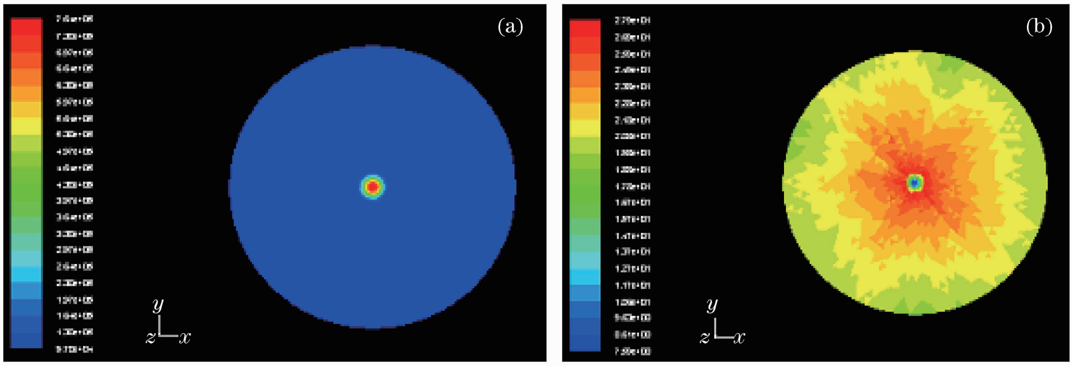

Fig. 9 Flow filed distributing of single nozzle model under the impact angle of 90°. (a) Wall pressure distribution; (b) wall velocity distribution

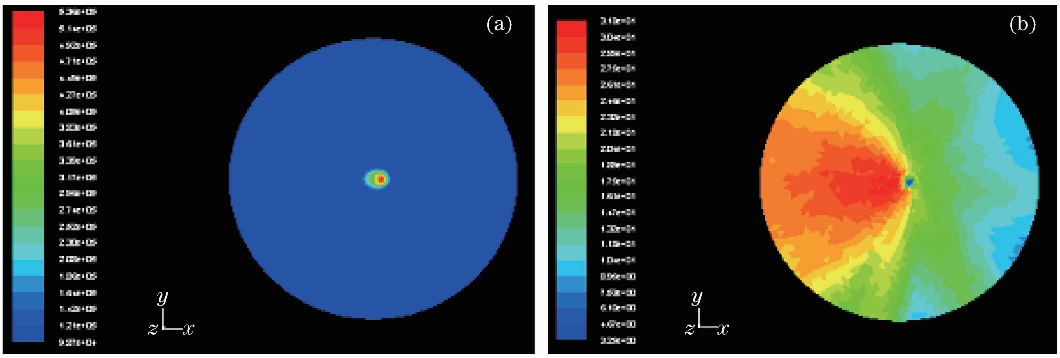

Fig. 10 Flow filed distributing of single nozzle model under the impact angle of 45°. (a) Wall pressure distribution; (b) wall velocity distribution

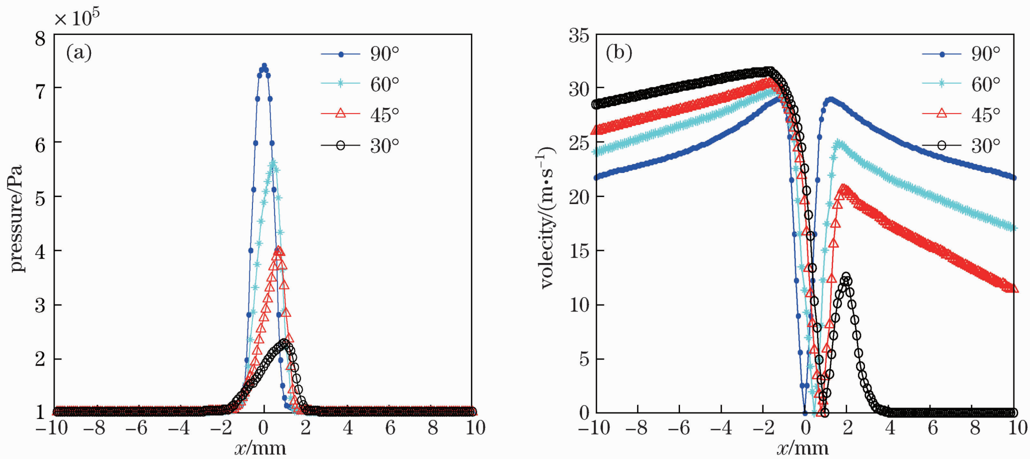

Fig. 11 Flow filed distributing on x-axis of single nozzle models. (a) Wall pressure distribution; (b) wall velocity distribution

In the jet polishing process, the mechanism of material removal is mainly the pressure in the vertical direction makes the abrasive particles on the wall pressed into workpiece a certain depth, the transverse velocity on the wall provides the abrasive particles a cutting force to achieve removal of material. The relationship between the amount of material removal and pressure and velocity are as follows:

$$\Delta Z \propto [P(x,\theta) - P_k]u^2(x,\theta), \tag{5}$$

Where $p(x,\theta)$, $p(x,\theta)$ is the wall distribution function of the pressure and velocity associated with the impact angle, p_k is the critical pressure producing material removal. If the pressure in the vertical direction is too large, exceeding the critical value of cracks, material will produce brittle removal. The pressure decreases as impact angle reduced, while the downstream velocity values changed little. So the oblique impingement models often obtain better process results than the vertical impingement models. If the impact angle is too small, the pressure in the vertical direction will be too small to remove the material. Impact angle selected from 30°～ 45° can improve processing quality in ensuring the removal efficiency. The vertical and oblique impingement models of different nozzle structures were built for the analysis of flow field.

Equal space stagger arrangement method was often used in the multi-nozzle structure models, which can be considered as a combination of triangle arranged three-nozzle units. Taking three nozzle model as an example for multi-nozzle jet polishing flow field analysis. Nozzle spacing between nozzles are set as 5 mm in triangle arranged and linear arranged three-nozzle models. In order to ensure that maximum velocity in all the impingement regions of multi-nozzle models can reach that of a single nozzle model, the nozzle spacing must be greater than 4.44 mm [6]. If the nozzle spacing is too small, jets will get mixed, velocity in each impingement area will be seriously affected.

Figure 12 are wall pressure and velocity distribution contours of triangle arranged three-nozzle model under the impact angle of 90°. Three jets spread around after impinging on the wall. Fluid drains out along the middle gap of each nozzle after meet each other. Three jets impinging on the workpiece has reached the maximum velocity of about 30 m/s, which effectively improved the efficiency of jet polishing removal. But in the mutual area between each impingement regions, the velocity values get down to zero due to the interaction of each fluid.

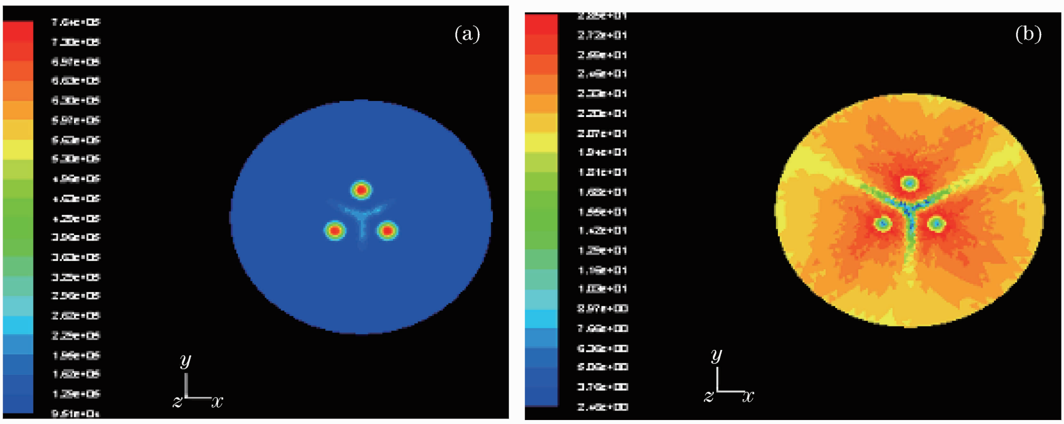

Fig. 12 Flow filed distributing of triangle arranged three-nozzle model under the impact angle of 90°. (a) Wall pressure distribution; (b) wall velocity distribution

Figure 13 are wall pressure and velocity distribution contours of triangle arranged three-nozzle model under the impact angle of 45°. The flow field of the nozzle at the top of the triangle was badly influenced by two jet flows under the bottom of triangle. The maximum velocity value in impingement region of the jet at the top of the triangle reduced to 20 m/s. The situation in multi-nozzle models of more than three nozzles is worse.

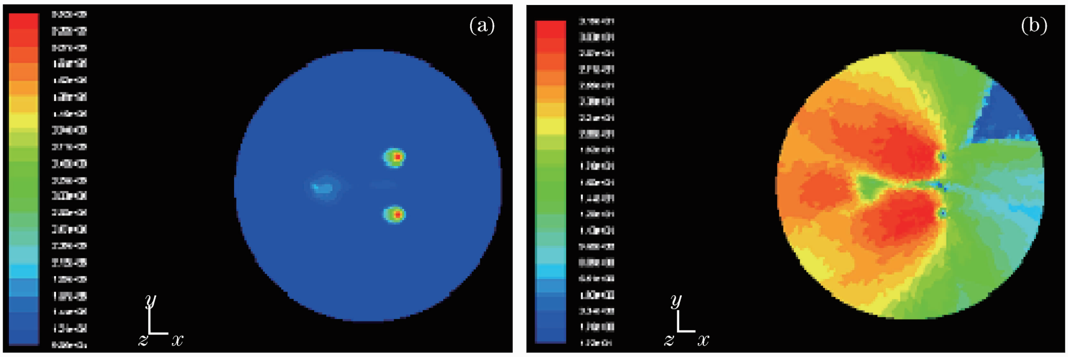

Fig. 13 Flow filed distributing of triangle arranged three-nozzle model under the impact angle of 45°.
(a) Wall pressure distribution; (b) wall velocity distribution

Figure 14 are wall pressure and velocity distribution contours of linear arranged three-nozzle model under the impact angle of 45°. The influence of each flow field between three jets is small. The maximum velocity values in impingement region of three jets totally get 30 m/s. However, the interaction in the mutual area between each impingement regions still exist, affect the uniformity of the whole processing.

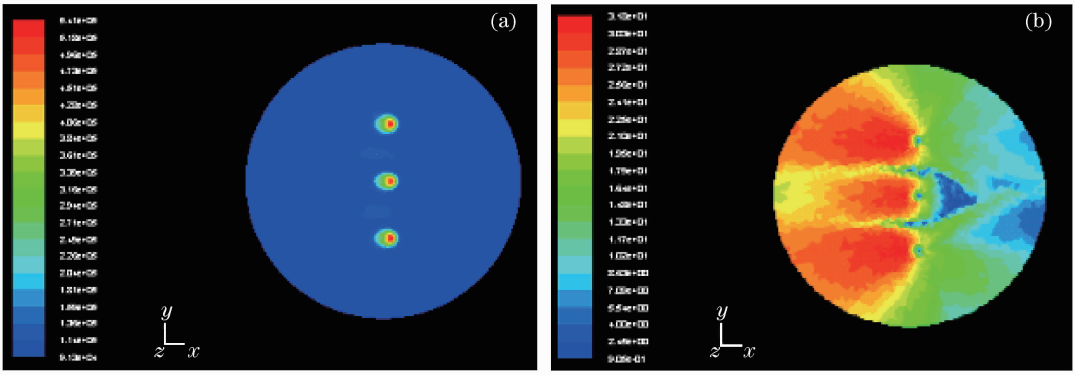

Fig. 14 Flow filed distributing of linear arranged three-nozzle model under the impact angle of 45°.
(a) Wall pressure distribution; (b) wall velocity distribution

Figure 15 are wall pressure and velocity distribution contours of vertical rectangular model. The flow field distribution on two sides of the nozzle is symmetrical under the impact angle of 90°. Figure 16 are wall pressure and velocity distribution contours of rectangular model under the impact angle of 45°. The downstream velocity value is 35 m/s. Velocity and pressure distribution of rectangular nozzle oblique impinging jet is uniform. It can effectively improve processing efficiency, and can achieve better processing effect.

5 Conclusion

Based on the fluid mechanics theory, circular single nozzle, rectangular nozzle and multi-nozzle structure jets under different impact angles are numerical simulated. The influence of impact angle on flow field of

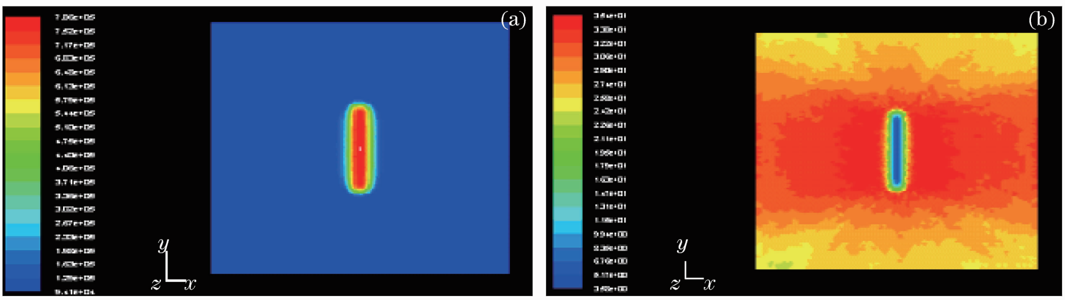

Fig. 15 Flow filed distributing of rectangular nozzle model under the impact angle of 90°.
(a) Wall pressure distribution; (b) wall velocity distribution

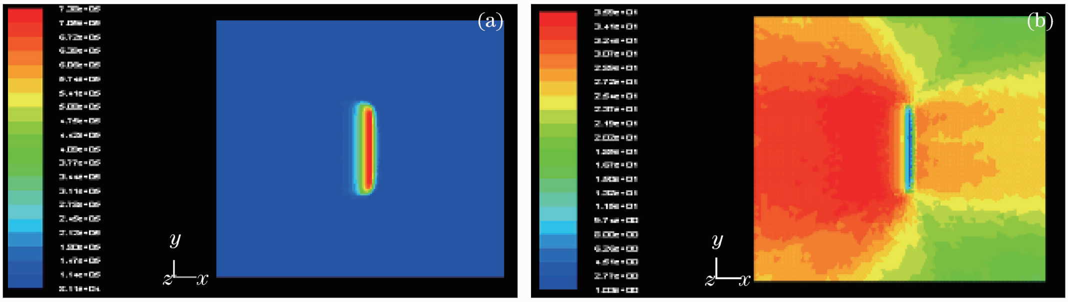

Fig. 16 Flow filed distributing of rectangular nozzle model under the impact angle of 45°.
(a) Wall pressure distribution; (b) wall velocity distribution

different nozzle structures is analyzed. As the impact angle decreases, the pressure and the upstream velocity decreases, while the downstream velocity value changes little. The large mutual influence between jets of triangle arranged oblique impinging model not conducive to the process; influence of each flow field between three jets of linear arranged model is small, but the nonuniformity of flow field also makes this method not good enough. Elongated nozzle model get the best flow field distribution. When using oblique impact jet for processing, linear arranged nozzle structure is superior to the triangle arranged nozzle structure, rectangular nozzle structure is superior to the multi-nozzle structure.

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