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Influence of nozzle exit tip thickness on the performance and flow field of jet pump †

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Abstract

The influence of exit tip thickness of nozzle δ_e on the flow field and performance of a jet pump was studied numerically in this paper. It is found that δ_e has influence on the distribution of turbulence kinetic energy k. If δ_e is ignored, k takes the highest value but dissipates rapidly than that of nozzle with a certain tip thickness. δ_e also affect apparently the development of tip vortex, which will occur near the exit tip of nozzle. The bigger the δ_e is, the larger the vortex is. The tip vortex develops with the increase of flow rate ratio q. When q=1 and δ_e=0.6~0.8mm, a small vortex will be found downstream the tip vortex. And a concomitant vortex happens down the tip vortex in the case of q=1 and δ_e=0.8mm. As q increases to 2, the downstream small vortex disappears and the concomitant vortex becomes bigger. It is also found that the tip vortex might interact with the possible backflow that formed in the throat tube and parts of suction chamber. The center of backflow was affect evidently by δ_e. With the increase of δ_e, the center of backflow under the same q will go downstream. When δ_e=0.4mm, the center of backflow goes farthest. Then, as the further increase of δ_e, the center of backflow will go back some distance. Although, δ_e has relatively great influence on the flow field within the jet pump, it exerts only a little impact on the performance of jet pump. When δ_e=0.2~0.6mm, the jet pump possess better performance. In most case, it is reasonable to ignore the nozzle exit tip thickness in performance prediction for the purpose of simplicity.

Keywords: Jet pump; Nozzle exit tip thickness; Numerical simulation; Tip vortex

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1. Introduction

The jet pump, or ejector, is a kind of fluid machinery and mixing reaction equipment that transfers momentum from a high velocity primary jet flow to a secondary flow. It typically consists of five main components, namely, driving and suction nozzle, suction chamber, mixing chamber or throat pipe, and diffuser, as schematically shown in Fig. 1. The absence of moving parts in jet pump results in many advantages over other kind of pumps as simple structure, easy to machine, low capital cost, convenience of operation and maintenance. The jet pump has also high reliability and adaptability for installation in remote or inaccessible locations to deal with poisonous, explosive, flammable or radioactive substance.

Nozzle is one of the most important parts of jet pump, which exerts an effect on the performance of jet pump directly and remarkably. The research on the nozzle influence was focus on its diameter and shape [1, 2]. Usually, the exit cross section of nozzle in a conventional jet pump is round and the exit tip thickness of the nozzle was determined empirically. In the design of a jet pump, the nozzle was considered to have enough exit tip thickness to resist possible erosion either by primary flow or by entrained flow in

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dealing with fluid containing particles. The nozzle should also have enough exit tip thickness δ_e to avoid possible damage during manufacturing and assembling. In view of fluid flow and mixing, many researchers thought that δ_e should be as thin as possible other than the requirement of manufacture. However, little work was found to determine quantitatively how δ_e should be chosen. Furthermore, δ_e was usually ignored in all the research work. This means that δ_e was taken as zero in both theoretical and simulating work. As mentioned before, the principle of jet pump is the turbulent mixing between primary jet and entrained flow. The velocity gradient at the nozzle exit section plays a very important role in the following turbulent mixing. This implies that δ_e might affect the flow field and then the performance of jet pump. Based on the situation, CFD works were carried out in this paper to figure out the influence of nozzle exit tip thickness δ_e on the flow field and performance of jet pumps.

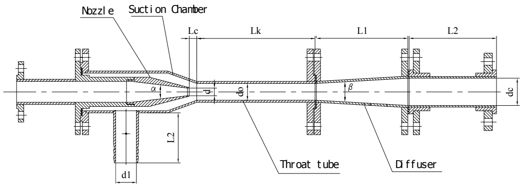


Fig. 1. Illustration of jet pump structure.

Where, d is outlet diameter of nozzle; d_0 is diameter of throat tube; d_c is outlet diameter of diffuser; L_c is nozzle-to-throat tube clearance; L_k is length of throat tube; L_1 is length of diffuser; α is convergent angle of nozzle; β is diffusive angle of diffuser.

2. Numerical simulation details

2.1 Turbulence model and governing equations

The flow within jet pump is assumed to be incompressible steady flow. The governing equations were Reynolds time-averaged Navier-Stokes equations and were closed by standard two-equation $k-\varepsilon$ turbulence model. So, the governing equations can be written as:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial}{\partial x_i}[\rho u_i u_j-(\mu+\mu_t)(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j})]=-\frac{\partial p}{\partial x_i}+\rho f_i \tag{2}$$

$$\frac{\partial}{\partial x_i}[\rho u_i k-(\mu+\frac{\mu_t}{\sigma_k})(\frac{\partial k}{\partial x_i})]=G-\rho\varepsilon \tag{3}$$

$$\frac{\partial}{\partial x_i}[\rho u_i \varepsilon-(\mu+\frac{\mu_t}{\sigma_\varepsilon})(\frac{\partial \varepsilon}{\partial x_i})]=C_{\varepsilon 1}G\frac{\varepsilon}{k}-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \tag{4}$$

Where, $\mu_t=C_\mu\rho\frac{k^2}{\varepsilon}$; $G=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$; and model coefficients are taken as c_μ=0.09, σ_k =1.0, σ_ε =1.3, $c_{\varepsilon 1}$ =1.44, $c_{\varepsilon 2}$ =1.92, respectively.

2.2 Model, grid and boundary conditions

The model of jet pump and the nozzle used in the simulation is shown in Fig. 1 and Fig. 2 respectively. Dimensions of jet pump are listed in Tab.1. The combination of throat tube and nozzle results in a jet pump of area ratio $m=6.27$.

Zhu, et al [3] found that the unsymmetrical configuration of suction chamber has a minute effect on the flow pattern near the nozzle, but exerts little effect on the performance of jet pump. As a simplification, the entrained flow was treated to entry the suction chamber in axial direction. So the jet pump itself and part of upstream and downstream connection tubes were chosen as the calculation region, as shown in Fig. 3. This means that the flow within the jet pump can be treated as symmetric flow.

In order to figure out the influence of δ_e, it varied from 0, 0.2, 0.4, 0.6, 0.8 to 1.0mm respectively, while the body of the pump and other dimensions of nozzle except δ_e were fixed as values listed in Table 1 and Fig. 2.

Table1. Dimensions of simulated jet pump.

D (mm)	d_0 (mm)	d_c (mm)	L_c (mm)	L_k (mm)	L_1 (mm)	L_2 (mm)	α (°)	β (°)
16	40.08	80	20	280	200	300	13.5	11.5

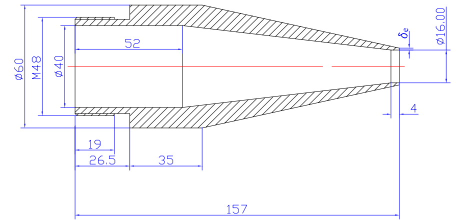


Fig. 2. Structure of nozzle.

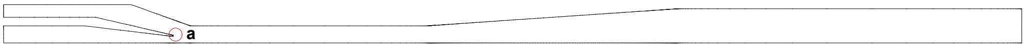


Fig. 3. Calculation region.

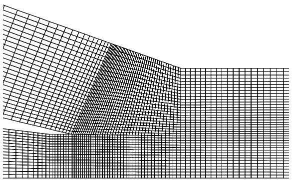


Fig. 4. Grid near nozzle.

Direction of the main flow was chosen as + Z and the center of exit section of the nozzle was set as the origin of coordinate system. The velocity gradient in the jet and wall boundary layer especially the zone near the nozzle is greater than other part of the flow field. So the grid near nozzle was distributed dense than other parts as shown in Fig. 4.

Boundary condition in the wall was treated as non-slip wall condition. The exit flow was considered as fully developed turbulence pipe flow. The axis of the jet pump was treated as symmetric boundary. The inlet flow was considered as uniform flow. The velocity of primary flow at inlet section was fixed and entrained flow velocity varied with calculation modes. The details can be found in next section. In the calculation, the finite volume method (FVM) and SIMPLE arithmetic was employed to solve the above equations.

3. Results and discussion

3.1 Performance parameter of jet pump

Usually, the performance of jet pump is expressed in terms of the following dimensionless parameters [4]:

(1) area ratio m

$$m = \frac{\text{Area of cross section of throat tube}}{\text{Area of cross section of nozzle outlet}} = (\frac{d_0}{d})^2 ,$$

(2) flow rate ratio q

$$q = \frac{Q_s}{Q_p} = \frac{\text{volumetric flowrate of entrained flow}}{\text{volumetric flowrate of primary jet}} ,$$

(3) pressure ratio h

$$h = \frac{\Delta p_d}{\Delta p_p} = \frac{(\frac{p_d}{\rho g} + \frac{v_d^2}{2g}) - (\frac{p_s}{\rho g} + \frac{v_s^2}{2g})}{(\frac{p_p}{\rho g} + \frac{v_p^2}{2g}) - (\frac{p_s}{\rho g} + \frac{v_s^2}{2g})} ,$$

(4) efficiency η

$$\eta = \frac{hq}{1-h} ,$$

Where p_d , p_s and p_p are the discharge, secondary flow and primary flow pressures; v_d , v_s and v_p are the discharge, secondary flow and primary flow velocities; ρ is water density; g is acceleration due to gravity.

3.2 Performance of jet pump with nozzles of different δ_e

As described before, in all the calculation, the primary flow velocity was fixed as 2.996 m/s, and the corresponding secondary flow velocities were varied from 0.109 m/s to 2.18 m/s respectively. The combination of velocities reached at different flow rate ratio q. In order to obtain the performance of jet pump, the flow field within it should be simulated first by above method under each operating modes. Then the dimensionless parameters, h , η can be calculated according to their definitions as described above.

The comparison of performance curves of jet pump between the calculated results, Semi-2D theory formula and experimental data can be found in [4] and [5]. So the feasibility of achieving the performance of jet pump by calculation was verified. In the same way, the simulated performance of jet pumps with nozzles of different δ_e can be also obtained as shown in the Figs. 5-6.

It is observed from above figures that the performance both the pressure ratio h and efficiency η of the jet pump at the same q varied a little with the change of δ_e. When δ_e=0.2 mm, jet pump had best performance, while the jet pump had the lowest performance if δ_e=1.0 mm. Considering the manufacture, δ_e=0.4 and 0.6 mm is also a better choice to possess a good performance. Calculation indicates that the maximum difference between the performance of jet pump with nozzle of a certain thickness ($\delta_e \neq 0$) and that of nozzle with no thickness (δ_e=0 mm) doesn't exceed 1.3%. This reveals that it is reasonable to ignore the nozzle exit thickness in most work of theoretical analysis and performance prediction for the purpose of simplicity.

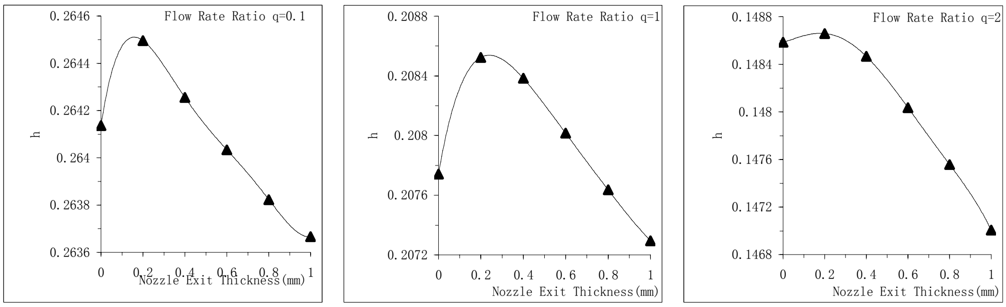


Fig. 5. $h \sim \delta_e$ Curve under different flow rate ratio q.

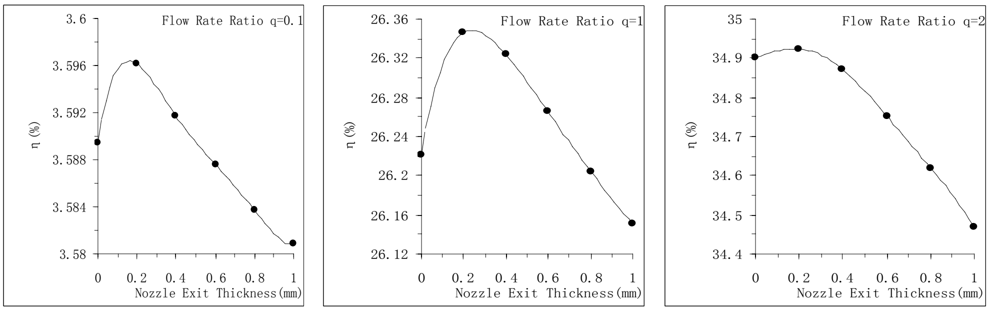
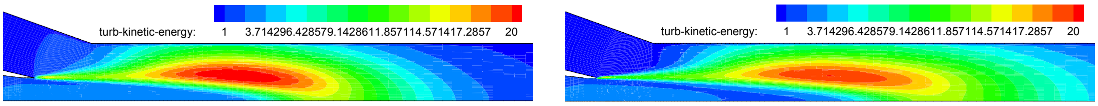
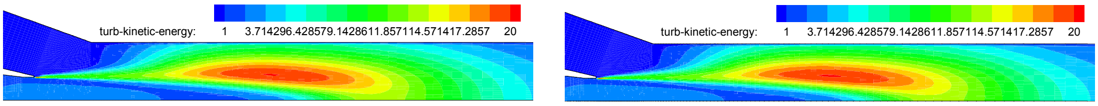


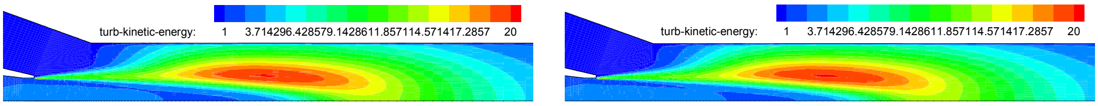
Fig. 6. $\eta \sim \delta_e$ Curve under different flow rate ratio q.



(a) δ_e=0 mm (b) δ_e =0.2 mm



(c) δ_e=0.4 mm (d) δ_e =0.6 mm



(e) δ_e=0.8 mm (f) δ_e =1 mm

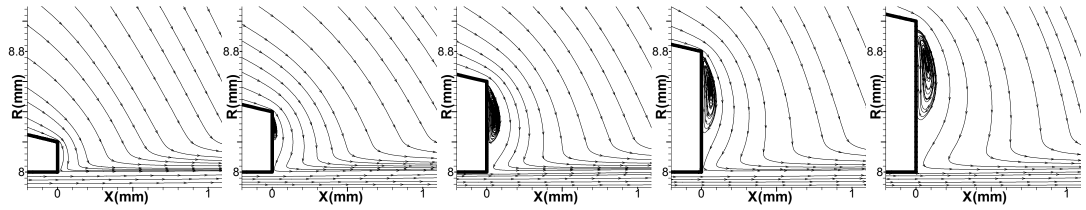
Fig. 7. Distribution of k with different δ_e, $q = 0.1$.

3.3 Influence of δ_e on the flow field distribution

Although δ_e has less effect on the performance, it did affect the flow field within the jet pump.

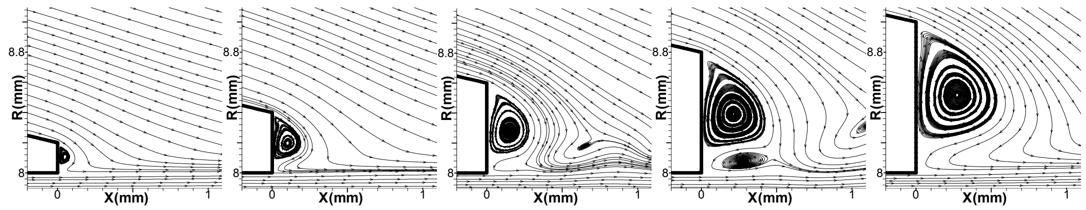
(1) Distribution of turbulence kinetic energy

Turbulence kinetic energy is an indicator of turbulent mixing. Fig. 7 presents the distribution of k in the throat tube and part of the suction chamber under $q = 0.1$. The development tendency of k with varied δ_e was the same. There are two peaks in the region. One is located in the nozzle exit. The other is located in the jet boundary layer some distance downstream the nozzle. When nozzle exit thickness is ignored (i.e. δ_e=0 mm), which has the maximum velocity gradient at the nozzle exit tip, the turbulence kinetic energy k has the highest intensity and the biggest high intensity region. This region indicates the taking place of strongest mixing. Downstream this region, k dissipates rapidly than other cases. The position of highest value of k is some near to the nozzle



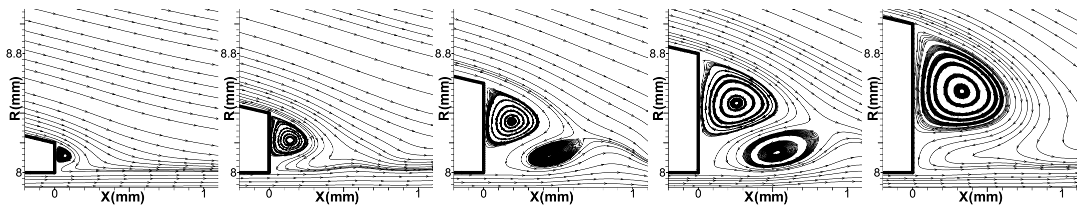
(a) δ_e =0.2 mm (b) δ_e =0.4 mm (c) δ_e =0.6 mm (d) δ_e =0.8 mm (e) δ_e =1.0 mm

Fig. 8 Flow field distribution around nozzle exit, q=0.1.



(a) δ_e =0.2 mm (b) δ_e =0.4 mm (c) δ_e =0.6 mm (d) δ_e =0.8 mm (e) δ_e =1.0 mm

Fig. 9. Flow field distribution around nozzle exit, q=1.



(a) δ_e =0.2 mm (b) δ_e =0.4 mm (c) δ_e =0.6 mm (d) δ_e =0.8 mm (e) δ_e =1.0 mm

Fig. 10. Flow field distribution around nozzle exit, q=2.

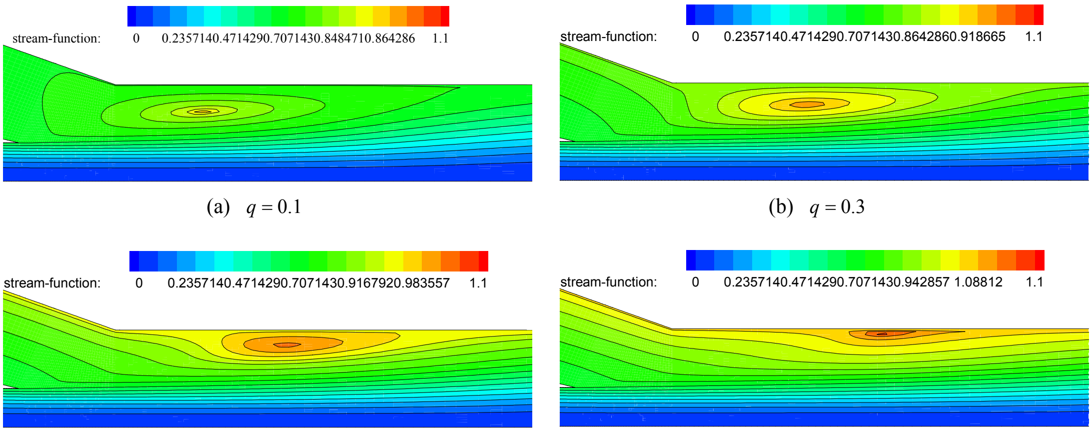
exit compared with that of nozzle with a certain exit tip thickness. Combined with Fig. 5 and Fig. 6, it reveals that stronger turbulent mixing indicates better mixing effect but also results in larger friction loss. To achieve a better efficiency, the mixing effect and friction loss should reach at a balance. Fig. 7(b)-(d) present a better distribution of k that has a corresponding higher efficiency. The calculated results in other flow rate ratio q also indicate the same conclusion.

(2) Flow field near nozzle tip

The flow field near exit tip of nozzle (region **a** in Fig. 3) can be found in the following enlarged figure. When nozzle exit tip thickness is ignored, there is no vortex near nozzle tip in all flow rate ratio q. When jet pump works at the status of q=0.1 as illustrated in Fig. 8, there is no vortex near the tip if δ_e =0.2 mm. With the increase of δ_e, tip vortex will occur. The tip vortex starts at the outer tip of nozzle and ends in half to about 3/4 of the exit tip length. The bigger the δ_e is, the bigger the vortex is.

As shown in Fig. 9, an obvious small vortex will appear near the tip of nozzle when q=1 and δ_e=0.2 mm. With the increase of δ_e, tip vortex develops bigger. A small vortex occurs downstream the tip vortex as δ_e=0.6 mm. As δ_e increases to 0.8 mm, a concomitant vortex that locates down the bigger tip vortex happens apart to above mentioned small downstream vortex. While, as δ_e increases to 1.0 mm, both the concomitant vortex and small downstream vortex disappear.

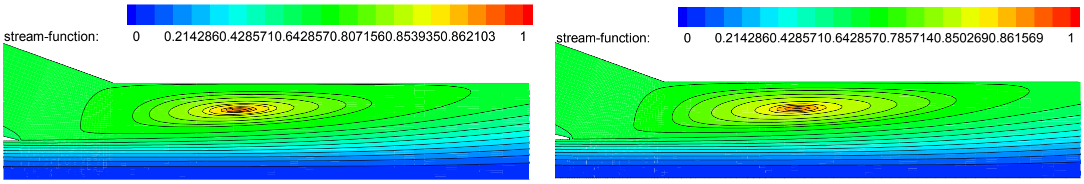
When jet pump works at the status of q=2, the development of tip vortex behaves a little different as illustrated in Fig. 10. Compared to the case of q=1, all vortex becomes bigger. The small downstream vortex, which occurs in Fig. 9(c)-(d) when q=1, disappears. In Fig. 10(c), the small vortex locating down the tip vortex evolves to a bigger concomitant vortex. Above figures demonstrate the bigger influence of δ_e on the development of tip vortex in different working status.



(a) $q = 0.1$ (b) $q = 0.3$

(c) $q = 0.5$ (d) $q = 0.7$

Fig. 11. Stream function of different q, δ_e =0 mm.



(a) $\delta_e = 0.2$ mm (b) δ_e =0.4 mm

Fig. 12. Stream function of different δ_e, $q = 0.1$.

(3) Stream function distribution

For a jet pump working in different case, there will be backflow in the throat pipe. Long, et al [6] found that the center of backflow, separation and reattachment point will vary with q. As shown in Figs. 8-11, the flow field near the nozzle exit tip is affected by δ_e. The development of the vortex near the tip might have interaction with the development of downstream separation flow that might happen in the throat tube and part of suction chamber. The evolvement of separation flow in jet pump as δ_e=0 under the flow rate ratio $q = 0.1 \sim 0.7$ can be found in Fig. 11. From this figure, one can see that the center of backflow goes downstream with the increase of q. While the distance between separation and reattachment point, i.e. the range of separation flow, decreases with the increase of q. Under the flow rate ratio $q = 0.1$, the separation even extends to the suction chamber. As a comparison, the stream functions in the jet pump of δ_e=0.2 mm and δ_e=0.4 mm under the same q were illustrated in Fig. 12. One can find that the range and center of separation flow exhibit some different. This reveals the strong interaction between separation flow in throat tube and the tip vortex. Furthermore, the center of backflow in jet pump of different δ_e under different q was shown in Fig. 13. It indicates clearly that the center of backflow was affect by the exit tip thickness δ_e. With the increase of δ_e, the center of backflow under the same q will go downstream first. The center of backflow goes farthest when δ_e=0.4 mm. Then, as the further increase of δ_e, the center of backflow will go back some distance.

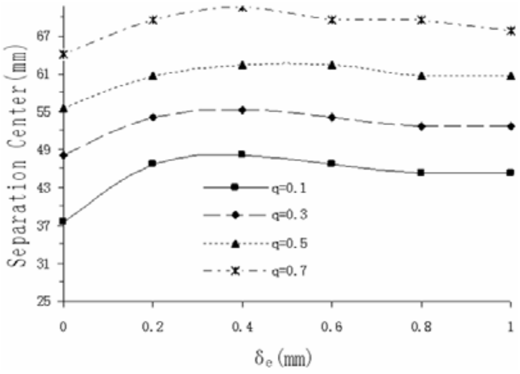


Fig. 13. Relationship between δ_e and separation center.

4. Conclusion

Nozzle is one of the most important parts of jet pump. In most of theoretical and simulation work, the nozzle exit tip thickness δ_e were ignored. In this paper, the influence of δ_e on the flow field and performance of jet pump were calculated numerically. It is found that δ_e affect greatly the development of tip vortex near the tip of nozzle, the distribution of turbulence kinetic energy and the backflow that might be occur in some working status. Although δ_e alters the flow field within throat tube, it exerts only a little influence on the performance of jet pump. When δ_e=0.2-0.6 mm, the jet pump possess better performance.

Acknowledgments

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