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Analysis and Numerical Simulation of the Stable Helical Vortex in TCP Flow in Vertical Screw Conveyor

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Abstract: The air in vertical screw conveyor creates flows such as Taylor-Couette-Poiseuille flow and turbulent flow with the increase of rotational speed of screw shaft. The stable helical vortex in TCP flow is beneficial to improve the transporting efficiency of granular materials. This paper described the N-S equations of incompressible steady flow (air) in vertical screw conveyor and deduced the distribution solution of velocity of stable helical vortex in TCP. And this paper also analyzed the relationship between the Reynolds number Re and parameters such as rotational speed of screw shaft, shaft diameter of screw shaft, screw pitch. Then this paper simulated different flows using FLUENT software and obtains the velocity vector chart and streamline chart with different rotational speed of screw shaft in vertical screw conveyor. The effect of simulation verified the correctness of theoretical analysis and recommended the critical Reynolds number Re_c suitable for appearance of stable helical vortex in TCP flow in the conveyor. *Copyright © 2013 IFSA.*

Keywords: Vertical screw conveyor, Taylor-Couette-Poiseuille flow, Stable helical vortex, N-S equations.

1 Introduction

The gap in two relative rotating concentric cylinders produce a secondary flow (the famous Taylor vortex), which is known as Taylor-Couette flow (TC) [1-3]. When the outer cylinder is stationary, if the inner cylinder rotates at a low rotating speed, the flow moves circularly in horizontal plane around the cylindrical axis, which is called the basic couette flow. When the angular velocity of the inner cylinder reaches a critical value, couette flow begins to lose stability. Then the new axisymmetric steady flow emerges, which is distributed vortex along the axial direction and adjacent vortex are reverse. The flow above is called as Taylor-Couette flow, which only moves along circumferential direction without axial direction. If an axial force is exerted on the movement, Taylor-Couette flow achieves simultaneously circumferential speed and axial speed, which is called as Taylor-Couette-Poiseuille flow (TCP) [4-7]. TCP flow can appears some vortexes such as laminar Taylor vortex, stable helical vortex and fluctuant helical vortex with the increase of Reynolds number [8-10]. When the Reynolds number continues to increase, the flow will appears wide range of disorder, which is called as the turbulent flow.

If we change modeled structure of the classic couette flow, translating the pressure forced from external into the pressure formed by own movement, which makes the flow moves upwards spirally. So adding vane to the inner cylinder in the modeled structure of the classic couette flow, which also is the structure of vertical screw conveyor. The theory of vertical screw conveyor will be described by the classic couette flow model modified. The high-speed rotation of screw shaft enables the flow of air around it to move, generating external pressure effecting on the classic couette flow. The external pressure is easy to be translated into the pressure formed by own movement. The vertical screw conveyor is a conveyor without flexible traction components. It drives materials to move relaying on the rotation of the screw shaft in a closed duct. The traditional conveying theory is described as follows: the centrifugal force generated by rotational screw vane effecting on granular materials and the force of friction between granular materials and the duct overcome gravity of granular materials, which make the granular materials are not dropped, but are lifted [11-14]. When the granular material is small, the interaction between granular materials and air becomes not be ignored. And the movement becomes more complex.

The theoretical and experimental research on the screw conveyor was started before appearance of screw ship unloader. Western scholars Vierling and Sinha put forward elemental point theory of screw conveying mechanism, which simplified the granular material on the surface of the screw as a single particle to analyze its movement and force. They introduced the concept of critical speed, and put forward the analytical method of solving rising speed of granular material. But they ignored the diversity of composition of particles, and the pressure distribution of granular material on the pipe wall of vertical screw conveyor and the surface of the screw. Swedish scholar Nilsson and Finland scholar Rademacher took granular material as ideal fluid by use of fluid mechanics theory. They analyzed the regularity of flow of granular material, and got analytical solution of free surface and pressure distribution. But they ignored the difference between granular material and ideal fluid, which inevitably lead to error between theoretical analysis and reality. In view of the limitations of these theories, the western academics Hans Gabier and Bttcher took particles as the object, and put forward the stack state of granular material on the surface of screw will change with the rotational speed of screw. The theoretical result is closer to reality, but still is not conform to the actual situation of the screw ship unloader [15-16].

The existing theory of vertical screw conveyor ignores that the stable helical vortex in TCP of air can be formed under the action of the high-speed rotating screw shaft in the vertical screw conveyor, but whose flow is beneficial to improve the transporting efficiency of granular materials. This paper studies formation conditions of the stable helical vortex in TCP of air, which lay the foundation for study of gas-solid two-phase stable helical vortex in TCP.

2. Mathematical Equations and Characteristic Parameter

2.1. Mathematical Equations

Navier-Stokes equations for incompressible viscous fluid in the form of cylindrical coordinates are as follows:

$$\begin{cases} \dfrac{\partial u_r}{\partial t}+u_r\dfrac{\partial u_r}{\partial r}+\dfrac{u_\theta}{r}\dfrac{\partial u_r}{\partial \theta}-\dfrac{u_\theta^2}{r}+u_z\dfrac{\partial u_r}{\partial z} \\ =f_r-\dfrac{1}{\rho}\dfrac{\partial P}{\partial r}+\mu\left(\nabla^2 u_r-\dfrac{2}{r}\dfrac{\partial u_\theta}{\partial \theta}-\dfrac{u_r}{r^2}\right) \\ \dfrac{\partial u_\theta}{\partial t}+u_r\dfrac{\partial u_\theta}{\partial r}+\dfrac{u_\theta}{r}\dfrac{\partial u_\theta}{\partial \theta}-\dfrac{u_r u_\theta}{r}+u_z\dfrac{\partial u_\theta}{\partial z} \\ =f_\theta-\dfrac{1}{r\rho}\dfrac{\partial P}{\partial \theta}+\mu\left(\nabla^2 u_\theta-\dfrac{2}{r}\dfrac{\partial u_r}{\partial \theta}-\dfrac{u_\theta}{r^2}\right) \\ \dfrac{\partial u_z}{\partial t}+u_r\dfrac{\partial u_z}{\partial r}+\dfrac{u_\theta}{r}\dfrac{\partial u_z}{\partial \theta}+u_z\dfrac{\partial u_z}{\partial z} \\ =f_z-\dfrac{1}{\rho}\dfrac{\partial P}{\partial z}+\mu\nabla^2 u_z \end{cases}, \quad (1)$$

where $\nabla^2=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}+\frac{\partial^2}{\partial z^2}$, r, θ, z are the cylindrical coordinate of the spatial point, u_r, u_θ, u_z are three coordinate components for speed, ρ is the fluid density, μ is the kinetic viscosity coefficient, P is the dynamic pressure for viscous fluid.

As shown in Fig. 1, we set the radius of screw shaft and the inner walls of duct are R_1 and R_2 respectively and the screw shaft rotates at an angular velocity ω. And we set origin on the screw shaft and Z-axis on the direction of screw shaft. (r, θ, z) is set as the column coordinate vector. The physical component of the fluid velocity is u =(u_r, u_θ, u_z).

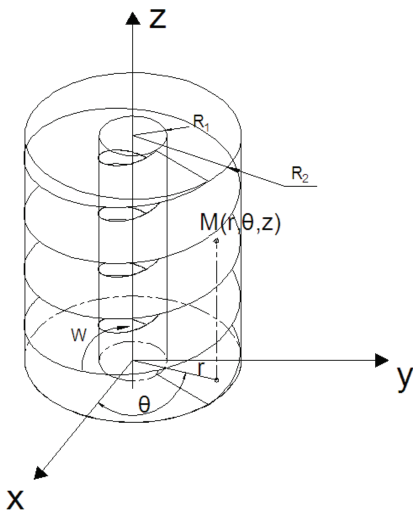

Fig. 1. Chart for the vertical screw conveyor in the form of cylindrical coordinates.

If mass force of air in vertical screw conveyor is ignored and the angular velocity of the screw shaft is constant, then $f_r = f_\theta = f_z = 0$, $\frac{\partial}{\partial t} = 0$.

Applying the initial condition above to Eq.1, the corresponding N-S equations can be expressed as follows:

$$\begin{cases} u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{u_\theta^2}{r}+u_z\frac{\partial u_r}{\partial z} \\ =-\frac{1}{\rho}\frac{\partial P}{\partial r}+\mu\left(\nabla^2 u_r-\frac{2}{r}\frac{\partial u_\theta}{\partial \theta}-\frac{u_r}{r^2}\right) \\ u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}-\frac{u_r u_\theta}{r}+u_z\frac{\partial u_\theta}{\partial z} \\ =-\frac{1}{r\rho}\frac{\partial P}{\partial \theta}+\mu\left(\nabla^2 u_\theta-\frac{2}{r}\frac{\partial u_r}{\partial \theta}-\frac{u_\theta}{r^2}\right) \\ u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z} \\ =-\frac{1}{\rho}\frac{\partial P}{\partial z}+\mu\nabla^2 u_z \end{cases} \quad (2)$$

If the flow in vertical screw conveyor is stable helical vortex in TCP, the initial conditions are described as: $\frac{\partial}{\partial\theta}=\frac{\partial}{\partial z}=\frac{\partial}{\partial t}=0$, $u_r=0$, $u_\theta=u_\theta(r,z)$, $u_z=u_z(r,z)$, $P=P(r,z)$.

Applying these conditions to Eq. 2, Eq. 2 can be simplified as follows:

$$\begin{cases} -\frac{u_\theta^2}{r}=-\frac{1}{\rho}\frac{\partial P}{\partial r} & (3\text{-}1) \\ 0=\mu\left(\frac{\partial^2 u_\theta}{\partial r^2}+\frac{1}{r}\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r^2}\right) & (3\text{-}2) \\ 0=-\frac{1}{\rho}\frac{\partial P}{\partial z}+\mu\left(\frac{\partial^2 u_z}{\partial r^2}+\frac{1}{r}\frac{\partial u_z}{\partial r}\right) & (3\text{-}3) \end{cases}$$

Eq.3-2 can be changed to:

$$\mu\left(\frac{\partial^2 u_\theta}{\partial r^2}+\frac{1}{r}\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r^2}\right)=\frac{\partial}{\partial r}\left(\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\right)=\frac{\partial}{\partial r}\left(\frac{\partial (r u_\theta)}{r dr}\right)=0$$

$$\frac{\partial (r u_\theta)}{r\partial r}=C_1(z)$$

$$\therefore u_\theta + r\frac{\partial u_\theta}{\partial r}=rC_1(z)$$

$$\therefore u_\theta(r,z)=\frac{r}{2}C_1(z)+\frac{C_2}{r} \quad (4)$$

If Mass force of air in vertical screw conveyor is ignored when screw shaft rotates, the force of friction and the centrifugal force effecting on air can be ignored. So the air suffers mainly the thrust perpendicular to screw surface, obtaining upward velocity and rotating around the screw shaft. The distribution of velocity is as shown in Fig. 2.

Where Φ is the screw angle, u_c is the velocity perpendicular to the screw surface generated by thrust. It can be decomposed into two velocity component: velocity component u_θ along the direction of θ and velocity component u_z along the direction of z.

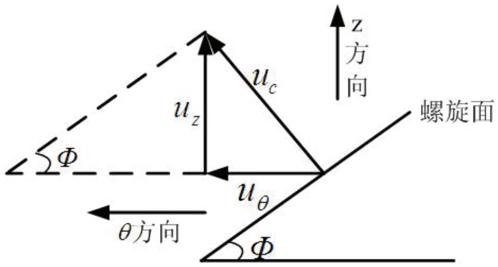

Fig. 2. The distributing diagram of velocity of air in vertical screw conveyor.

Thus the boundary conditions for stable helical vortex in TCP in vertical screw conveyor is

$$\begin{cases} u_\theta\big|_{r=R_1}=\omega R_1 \\ u\big|_{r=R_2}=0 \\ tan\Phi=\frac{u_\theta}{u_z}=\frac{S}{2\pi r} \end{cases}$$

where ω is the angular velocity of screw shaft, Φ is the screw angle, S is the screw pitch.

Applying the boundary conditions to Eq.4:

$$\begin{cases} \frac{R_1}{2}C_1(z)+\frac{C_2}{R_1}=\omega R_1 \\ \frac{R_2}{2}C_1(z)+\frac{C_2}{R_2}=0 \end{cases}$$

$$\therefore C_1(z)=-\frac{-2\omega R_1^2}{R_2^2-R_1^2}$$

$$C_2=\frac{\omega R_1^2 R_2^2}{R_2^2-R_1^2}$$

$$\therefore u_\theta=\frac{r}{2}c_1(z)+\frac{C_2}{r}=\frac{\omega R_1^2(R_2^2-r^2)}{r(R_2^2-R_1^2)} \quad (5)$$

Thus the distribution solution of velocity for stable helical vortex in TCP in vertical screw conveyor is

$$\begin{aligned} u&=\sqrt{u_\theta^2+u_z^2}=u_\theta\sqrt{1+\frac{4\pi r^2}{S^2}} \\ &=\frac{\omega R_1^2(R_2^2-r^2)}{r(R_2^2-R_1^2)}\sqrt{1+\frac{4\pi r^2}{S^2}} \end{aligned} \quad (6)$$

2.2. The Characteristic Parameter of Hydrodynamics

The characteristics of hydrodynamics of TCP flow is described by the Reynolds number Re.

Reynolds number can distinguish flow characteristics and whether the flow is laminar or turbulent. So the critical parameters of different flow in vertical screw conveyor can be described by the Reynolds number.

Calculation formula of Reynolds number of abnormal pipe is as follows:

$$Re = \frac{\bar{u}d}{v} \tag{7}$$

where $\bar{u}$ is the average velocity perpendicular to the flowing section, v is the kinetic viscosity coefficient, d is the hydraulic diameter of abnormal pipe, which is defined as follows:

$$d = \frac{4A_s}{x} \tag{8}$$

where A_S is the area of flowing section, x is the wetted perimeter.

The formula of flow passing flowing section in unit time is as follows:

$$Q = \iint_{A_S} \bar{u}\,dA_S = \iint_A \bar{u}_n\,dA \tag{9}$$

where A is the section of flow in any direction, that is $dA_s = \cos(\bar{u}, n)dA$. $\bar{u}_n$ is average normal velocity perpendicular to A, that is $\bar{u}_n = \bar{u}\cos(\bar{u}, n)$. So Eq.7 and Eq.8 can be changed to:

$$Re = \frac{\bar{u}_n d}{v} \tag{10}$$

$$d = \frac{4A}{x} \tag{11}$$

The formula of Reynolds number in vertical screw conveyor is deduced according to Eq. 10 and Eq. 11. The axial section of vertical screw conveyor as is shown in Fig. 3. The section between a pitch as shown as the shade region in Fig. 3 is analyzed. The flow is split longitudinally along the screw axis.

Hydraulic diameter in vertical screw conveyor is

$$d = \frac{4A}{x} = \frac{4(R_2 - R_1)S}{2(R_2 - R_1 + S)} = \frac{2S(R_2 - R_1)}{R_2 - R_1 + S} \tag{12}$$

Reynolds number in vertical screw conveyor is

$$Re = \frac{\bar{u}_n d}{v} = \frac{2\bar{u}_n S(R_2 - R_1)}{v(R_2 - R_1 + S)} \tag{13}$$

As shown in Fig. 3, where R_1 and R_2 are the radius of screw shaft and the inner wall of duct respectively, S is the screw pitch, v is he kinetic viscosity coefficient, $\bar{u}_n$ is average normal velocity perpendicular to the section, that is average velocity component $\bar{u}_\theta$ along the direction of θ.

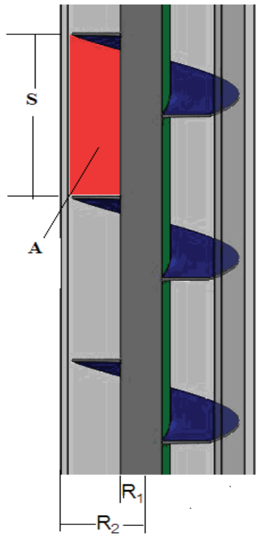

Fig. 3. The section between a pitch in vertical screw conveyor.

Let $\bar{u}_n = \bar{u}_\theta = \frac{1}{R_2 - R_1}\int_{R_1}^{R_2} u_\theta dr$, applying Eq.5 to it, then

$$\begin{aligned}\bar{u}_n &= \frac{1}{R_2 - R_1}\int_{R_1}^{R_2} u_\theta dr = \frac{1}{R_2 - R_1}\int_{R_1}^{R_2} u_\theta dr = \\ &= \frac{\omega R_1^2}{(R_2^2 - R_1^2)(R_2 - R_1)}\int_{R_1}^{R_2} \frac{R_2^2 - r^2}{r} dr = \\ &= \frac{\omega R_1^2}{(R_2^2 - R_1^2)(R_2 - R_1)}(R_2^2 \ln r - \frac{1}{2}r^2)\Big|_{R_1}^{R_2} = \\ &= \frac{\omega R_1^2[R_2^2 \ln\frac{R_2}{R_1} - \frac{1}{2}(R_2^2 - R_1^2)]}{(R_2^2 - R_1^2)(R_2 - R_1)}\end{aligned} \tag{14}$$

3. Fluent Numerical Simulation and Analysis of Result

3.1. Calculation Model

Building model as shown in Fig. 4, the gap G between screw vane and inner wall of duct is 2 mm, the radius of screw shaft R_1 is 50 mm, the radius of inner wall of duct R_2 is 155 mm, the screw pitch S is 110 mm and the model height is 330 mm. Simulating the model above using FLUENT, whose material is the air, that is the condition of vertical screw conveyor is idling. The kinetic viscosity coefficient v of air between screw shaft and inner wall of duct is 1.4850e-05 m^2/s. The duct is motionless while the screw shaft rotating. We can obtain different velocity vector chart and streamline chart under different rotating speed by calculation of k-e turbulence model.

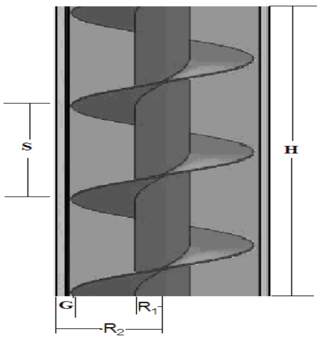

Fig. 4. The calculation model of vertical screw conveyor.

3.2. Mesh Generation

After modeling of main body of screw conveyer is set up by SOLIDWORK, it is imported to the former processor of GAMBIT to complete modeling of other parts, mesh generation and set up of boundary conditions.

When the screw vane rotates with the screw shaft, shape of the flow is changed along with time. Thus dynamic mesh is needed here. Compiling the file as the followings:

((dong 3 point
(time 0 1 60)
(omega_v $-\omega$, $-\omega$, $-\omega$)),

where ω is the angular velocity of screw shaft. It need read different file when the angular velocity is different.

3.3. Fluent Numerical Simulation

When simulating the flow of air in vertical screw conveyor by FLUENT software, the output wanted is the velocity vector chart and the streamline chat. And the critical Reynolds number is discussed between the stable helical vortex in TCP flow and other flow in vertical screw conveyor.

When the rotational speed of screw shaft is 0.5 r/s, the average velocity $\overline{u}_n$ along the direction of θ is 0.057 m/s by Eq. 14. The Reynolds number *Re* worked out is 412 by Eq. 13, whose velocity vector chart and the streamline chat is as shown in Fig. 5.

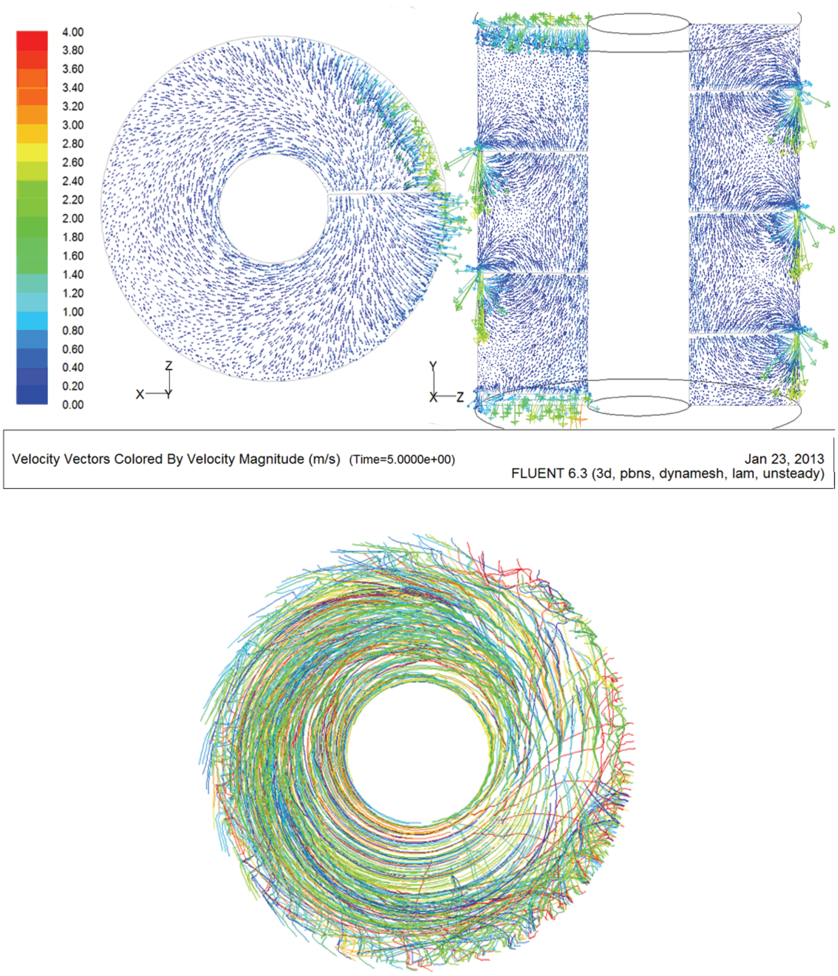

Fig. 5. The velocity vector chart and the streamline chat when the rotational speed of screw shaft is 0.5 r/s.

The velocity of air is as small as in the range of 0 m/s ~ 0.3 m/s because of small rotational speed. The flow in the streamline chat is stable. The flow shows laminar flow model but confused streamline between the screw vane and the inner wall of duct. The air obtains upward velocity and rotates around the screw shaft, which belongs to the stable helical vortex in TCP flow. The flow generates some vortex between the screw vane and the inner wall of duct, whose velocity is bigger.

When the rotational speed of screw shaft is 3r/s, the average velocity $\bar{u}_n$ worked out is 0.342 m/s and the Reynolds number *Re* worked out is 2470. The velocity vector chart and the streamline chat are as shown in Fig. 6. The velocity of air is in the range of 0 m/s ~ 1.8 m/s, which is bigger near the screw shaft. The flow in the streamline chat is stable, which shows laminar flow model. The air obtains upward velocity and rotates around the screw shaft, which belongs to the stable helical vortex in TCP flow.

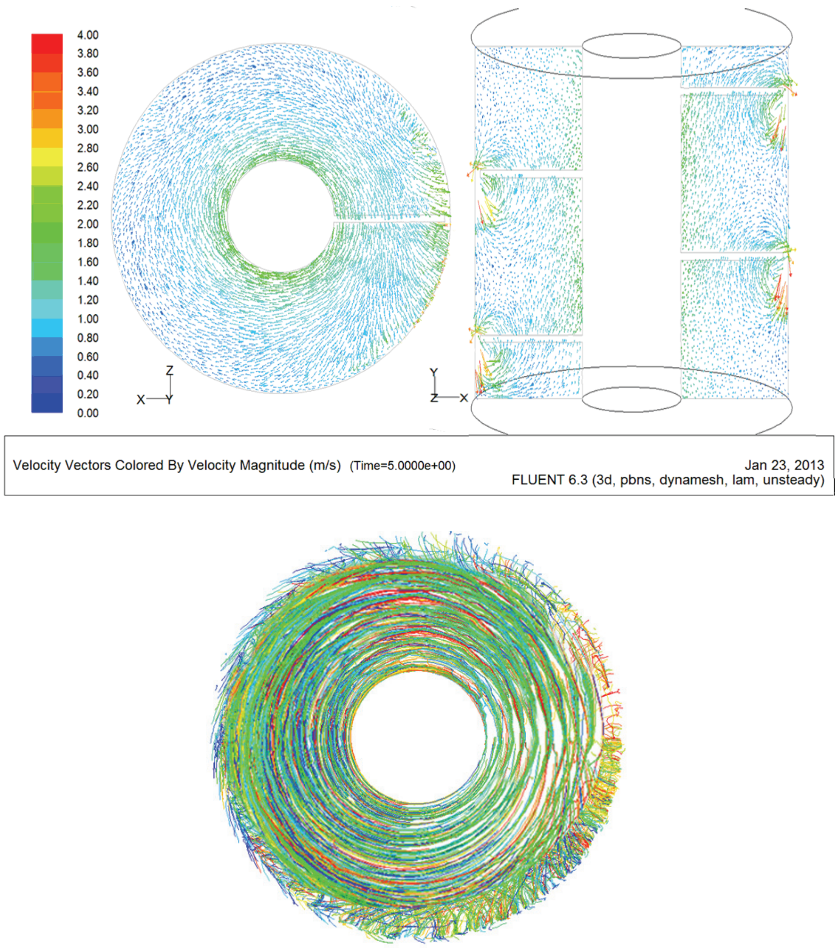

Fig. 6. The velocity vector chart and the streamline chat when the rotational speed of screw shaft is 3 r/s.

When the rotational speed of screw shaft is 6 r/s, the average velocity $\bar{u}_n$ worked out is 0.684 m/s and the Reynolds number *Re* worked out is 4950. The velocity vector chart and the streamline chat are as shown in Fig. 7. The velocity of air is in the range of 0 m/s ~ 3.5 m/s, which is bigger near the screw shaft. The flow in the streamline chat is stable, which shows laminar flow model. The air obtains upward velocity and rotates along the screw shaft, which belongs to the stable helical vortex in TCP flow. But compared with the streamline in Fig. 6, the flow generated some bigger random motion near inner wall of duct, which indicates the appearance of turbulence.

When the rotational speed of screw shaft is 9 r/s, the average velocity $\bar{u}_n$ worked out is 1.025 m/s and the Reynolds number *Re* worked out is 7410. The velocity vector chart and the streamline chat are as shown in Fig. 8. The velocity of air is in the range of 0 m/s ~ 5.2 m/s, which is bigger near the screw shaft. The streamline is disordered except for the streamline near the screw shaft. The flow layers adjacent produce slide and mix, which lead to damage of the laminar flow. The flow makes random motion and belongs to turbulence.

When the rotational speed of screw shaft is 1r/s, 2 r/s, 4 r/s, 5 r/s, the flow is similar to the flow in Fig. 6, which belongs to the stable helical vortex in TCP flow.

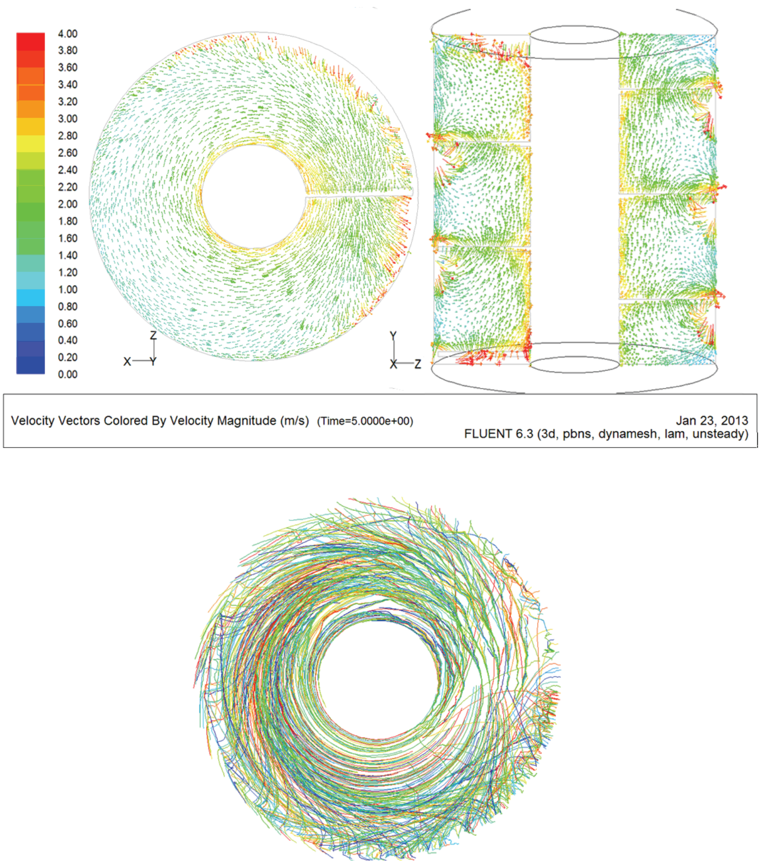

Fig. 7. The velocity vector chart and the streamline chat when the rotational speed of screw shaft is 6 r/s.

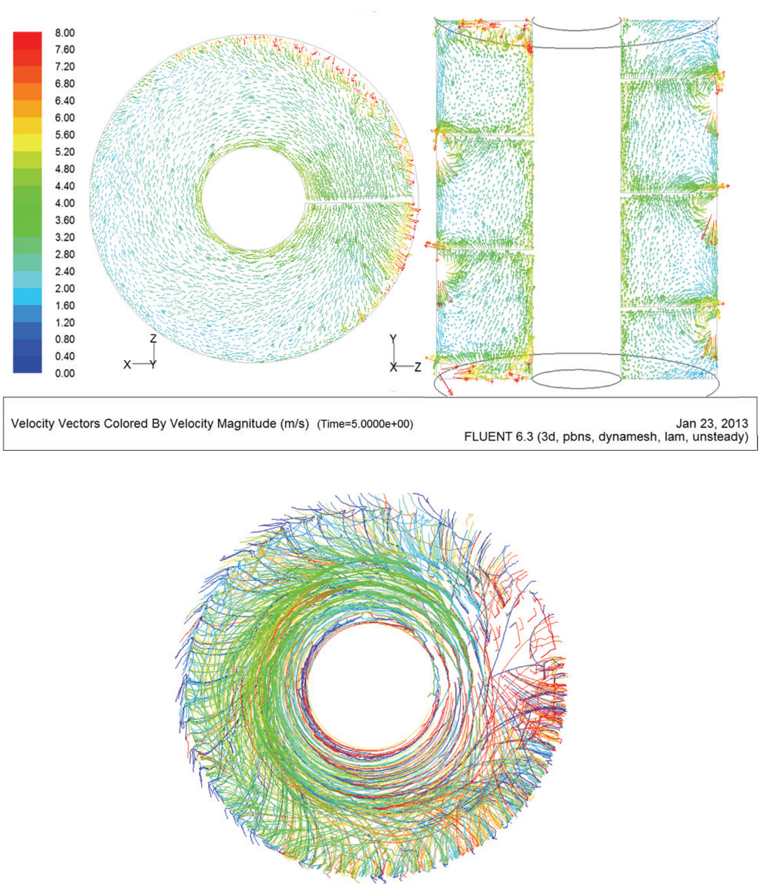

Fig. 8. The velocity vector chart and the streamline chat when the rotational speed of screw shaft is 9 r/s.

3.4. Analysis of Result

The flow in vertical screw conveyor belongs to the stable helical vortex in TCP flow when the Reynolds number *Re* within the range of 5000, which can improve the transporting efficiency of granular materials. So the critical Reynolds number Re_c suitable for appearance of stable helical vortex in TCP flow in the conveyor is 5000. When the Reynolds number *Re* is bigger than 5000, the flow may is adverse to transportation of granular materials.

The flow belongs to the stable helical vortex in TCP flow when the rotational speed of screw shaft is 3 r/s by result of numerical simulation. Taking five points from the flow above, the velocity of the numerical simulation and theoretical analysis by Eq. 14 are compared. The result is as shown in Table 1. The velocity error is small. And the velocity is bigger near the screw shaft, which proves the validity of theoretical analysis.

Table 1. Velocity comparison between numerical simulation and theoretical analysis.

The distance from the center line of the screw shaft (m)	0.055	0.079	0.103	0.127	0.150
The velocity of numerical simulation (m/s)	1.72	1.33	1.05	0.64	0.18
The velocity of theoretical analysis (m/s)	1.702	1.349	0.989	0.574	0.11

4. Conclusions

This paper describes the N-S equations of incompressible steady flow (air) in vertical screw conveyor and deduces the distribution solution of velocity of stable helical vortex in TCP. And this paper also analysis the relationship between the Reynolds number *Re* and parameters such as rotational speed of screw shaft, shaft diameter of screw shaft, screw pitch. Making numerical simulation and analysis to the flow of air in vertical screw conveyor, the effect of rotational speed on the flow is focused. Finally this paper recommends the critical Reynolds number Re_c suitable for appearance of stable helical vortex in TCP flow in the conveyor and providers the basis for architectonics of vertical screw conveyor.

Acknowledgements

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