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Numerical simulation of heat transfer and pressure drop characteristics in non-horizontal swirling tube

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ABSTRACT

In the non-horizontal pipeline flow, the fluid will accelerate (or decelerate) and contact with the heat exchange surface due to the influence of gravity. In this paper, the effects of different vane angles and Reynolds numbers on the heat transfer and pressure drop characteristics in the non-horizontal swirling tube are investigated by numerical simulation. It shows that the component force of gravity in the axial direction plays a key role in the heat transfer intensity and pressure drop. Compared with the horizontal flow, the cross-section temperature distribution of the non-horizontal flow changes significantly, and the pressure distribution changes moderately. These findings provide some theoretical guidance for the optimization of the structure of the swirler in a non-horizontal pipeline.

Keywords: Non-horizontal, Swirling tube, Heat transfer, Pressure drop, Numerical simulation

1. INTRODUCTION

Swirling flow is widely used in material separation[1], combustor[2], heat exchanger and pipeline heat transfer enhancement[3] and other fields. The principle of heat and mass transfer enhancement is to form unsteady flow and secondary flow effectively as vortex flow disturbance, promoting the mixing of vortex and the thinning of boundary layer, to achieve the effect of heat and mass transfer enhancement. However, during the heat transfer process of a swirling flow, there is an energy loss caused by swirler when heat transfer is strengthened. Therefore, the structural design and selection of a swirler component are important. Compared with rotating pipes[4], guided swirlers[5], tangential inlets[6] and other structures that generate vortices, and among them, the axial swirlers[7, 8]has its advantages in structure because of no moving parts, small occupied volume and easy installation and maintenance. At present, the axial swirler is considered as an ideal swirler.

Ahmadvand et al.[9] carried out experimental and CFD studies on the steady-state heat transfer and flow characteristics of the swirling flow generated by axial swirlers. It showed that the 30 °, 45 ° and 60 ° vane angle have increased in heat transfer performance by 50-110% compared to normal pipe flow. Weerapun and Somchai et al.[10] further evaluated the heat transfer and pressure drop characteristics of the pipe swirl generators by conducting an experimental study on the swirling decaying flow generated by the pipe swirl generators components. The results show that the increase of pressure drop is often greater than the increase of heat transfer. In addition, B. Chen et al.[7, 8] studied the heat transfer and hydrodynamic characteristics in the horizontal swirling tube. For all angles, it was found that the Reynolds number has little correlation with the system structure. G. Liang et al.[11]carried out a numerical study on the heat transfer and friction characteristics of the inner surface of a delta airfoil circular tube. It was investigated that the geometric configurations with the minimum frictional resistance have high heat transfer effect. This study helps to give insight of an optimal configurations for heat transfer and pressure drop in the swirling tube. E. taheran et al.[12]studied the effects of three swirl components with

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*Corresponding author. E-mail address: chenbm@dgut.edu.cn different torsion angles on the heat transfer intensity, friction coefficient and comprehensive heat transfer performance of tubular heat exchanger through experiments. The results showed that the variation of friction coefficient is greatly affected by the geometry of the swirl components and have high heat transfer intensity. But, the heat transfer performance is not necessarily better. H. Funahashi et al.[13]studied the variation rules of friction coefficients on the wall and interface under the gas-liquid two-phase swirling flow in the vertical pipe through experiments, and the friction factors were evaluated using measured pressure drop and the void fraction. Yet, the flow states are different between horizontal and vertical pipes, the parameters studied are relatively complex, and the functional relations between corresponding parameters are also different. For the non-horizontal pipeline flow, the fluid will accelerate (or decelerate) and contact with the heat exchange surface due to the influence of gravity.

In this paper, numerical simulation of the non-horizontal swirling flow generated by the axial swirlers is carried out to investigate the heat transfer and pressure drop characteristics of the swirling tube under the influence of different Reynolds numbers and vane angles. It provides some theoretical guidance for the optimization of the structure of the swirler and prediction of the heat transfer and pressure drop of the flow pattern in a non-horizontal pipeline.

2. Numerical simulation

2.1 Geometric model and physical problem description

The geometric physical model is shown in Fig. 1. The Vane angle (θ) expressed as 30 °, 45 ° and 60 °. The corresponding flow way number is 6, 8 and 10 respectively. The actual size of the swirlers and Pipeline's azimuth angle are shown in Fig.2. In order to quantify the influence of gravity and to represent the non-horizontal flow mode, we defined the Pipeline's azimuth angle as the angle between the inlet direction and the horizontal plane. In this paper, we study the Pipeline's azimuth angle values (α) respectively -90°, -60°, -45°, -30°, 0, 30°, 45°, 60°, 90°, the following discussion respectively expressed in number 1 ~ 9 corresponding to the Pipeline's azimuth angle of -90° ~ 90°.

A two-dimensional diagram of a swirling tube is shown in Fig. 3. The reference of the coordinates is located at the center of the inlet section, and the flow region is in the positive direction of the z-axis. The working medium used in this paper is water, which flows through the annular inlet at different speeds. After being pass through the swirler, it flows out of the swirler with a certain swirl intensity, generating a rotary eddy current and disturbing the flow field, and conducting heat transfer with the heating element. The heat transfer and pressure drop characteristics in the flow process were studied, and the heat transfer performance of the flow system was evaluated.

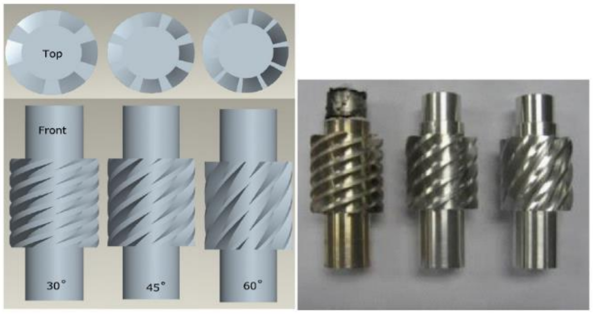


Fig. 1 Geometric model (left) and physical model (right)

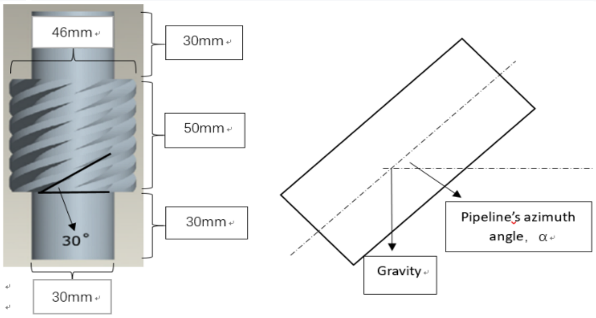


Fig. 2 The size of swirlers(left) and Pipeline's azimuth angle (right)

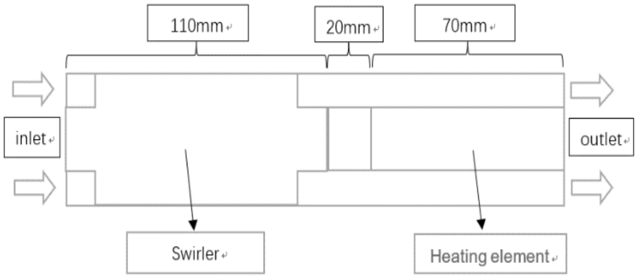


Fig. 3 Two-dimensional diagram of a swirling tube

2.2 Mesh generation and solution settings

Since this study focuses on the pressure drop and heat transfer of the fluid, the flow area of the loop tube and the flow passage part of the swirl component are combined into a whole as the fluid domain of the model[7, 8], and the solid part of the swirler is removed. The heating element was replaced with a heating wall without thickness, as shown in Fig. 4. Considering the complexity of flow field structure and the effective utilization of computer resources, ICEM16.0 was used to generate the fluid domain into hybrid grid. The flow passage is partly unstructured and the rest is structured. The mesh view is shown in Fig. 5.

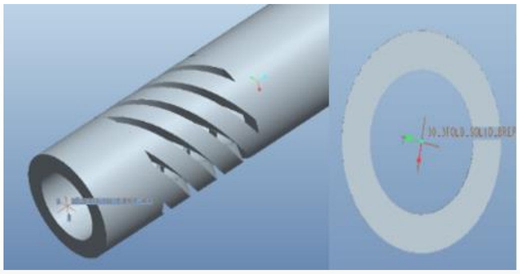


Fig. 4 Modified geometry model (fluid domain), full view (left), top view (right)

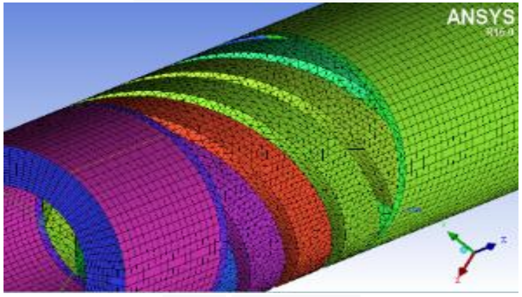


Fig. 5 Mesh view

It is assumed that the physical property of water is constant, the density is 1000kg/m3, the thermal conductivity is 0.61w /(m· K), the specific heat capacity is 4179J/(kg· K), and the dynamic viscosity is 0.001kg/(m· s). At both walls, the flow is prohibited from slipping and at the same time impermeable (u = v = 0). The heated wall was set at a constant temperature of 353K, and the remaining walls were all adiabatic. The model boundary are velocity inlet and outflow outlet. The pressure-based solver from Fluent 16.0 is used to solve the governing equation. The solution was calculated by an RNG turbulence model. The transient equation adopts the first order implicit format. The gradient term uses the discrete format based on the node, and the pressure term uses PRESTO!. QUICK format was adopted for the convection term and the second-order upwind format was adopted for the remaining terms. The standard of residual convergence is set as level 10^{-6}. In order to avoid the discontinuity of results due to excessively dense grids and to give a consistent solution for arbitrarily refined grids, the lower limit of Y+ is automatically restricted to 11.06[14] by using Scalable Wall Function. The setting of gravity term is shown in Table 1.

Table 1 The setting of gravity term (m/s^2)

α direction	-90°	-60°	-45°	-30°	0	30°	45°	60°	90°
X	0	4.9	6.93	8.487	9.8	8.487	6.93	4.9	0
Y	0	0	0	0	0	0	0	0	0
Z	9.8	8.487	6.93	4.9	0	-4.9	-6.93	-8.487	-9.8

2.3 Mesh and time independent

The mesh number and time step will have an impact on the accuracy of the calculation and the resource consumption of the computer. Excessive grids will increase the rounding error of calculation that is not only waste computer resources, but also decrease the accuracy. Insufficient of grids will not guarantee the calculation accuracy[15]. As the time step decreases further, rounding error dominates. Therefore, a solution with the short time step cannot be regarded as an accurate solution[16]. Hence, 8 sets of mesh Number and 5 sets of time step were set to exclude the influence of errors, and Nu and f were used as the validation criteria. According to the validation, when the mesh number is about 180,000 and the time step is 0.1s, Nu and f have little change. Therefore, in order to reduce the calculation time, the model with a mesh number of 180,000 and a time step of 0.1s was selected for calculation.

3. Results and discussion

Following section, the numerical simulation results will be discussed and analyzed to investigate the heat transfer and pressure drop characteristics to comprehend the heat transfer performance in swirling tube. The main parameters of interest in the study are the Nusselt number, friction factor, thermal enhancement factor (TEF)[17].

The Nusselt number is defined as

$$\mathrm{Nu} = hD_h/\lambda$$

Friction factor is a dimensionless concept to evaluate pressure drop,

$$\mathrm{f} = \frac{2D_h \bigtriangleup P}{L\rho u^2}$$

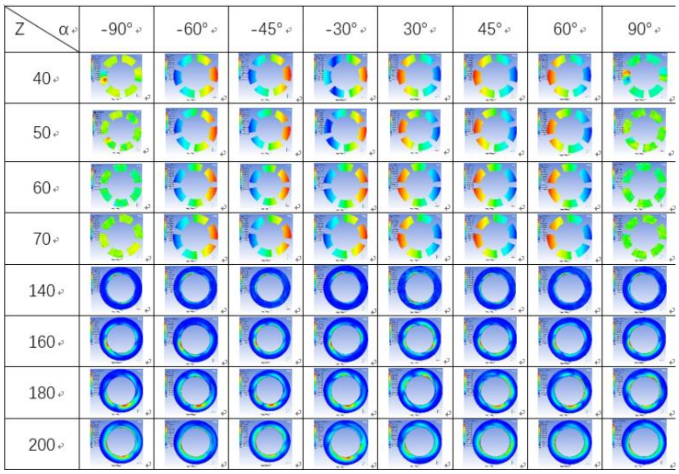
The ratio of heat transfer coefficient with vortex generator over heat transfer coefficient of smooth tube under the same pumping power is TEF,

$$\eta = \frac{(Nu/Nu_0)}{(f/f_0)^{1/3}}$$

3.1 Temperature and pressure distribution differences

The difference of temperature and pressure distribution between the non-horizontal state and the horizontal state in different axial distances are shown in Table 2. The differences of cross-section pressure distribution is increased linearly along the axial direction, but the differences of cross-section temperature distribution along the axial direction is high. This is due at the same α, the force component of gravity in the axial direction remains the same that resulted in a linear change in the pressure change along the axial direction. After the flow leaves the swirler, the heat and mass transfer effects are constantly influenced by the tangential velocity component and gravity component, resulting in more obvious changes in temperature.

Table 2 The difference of temperature and pressure distribution between the non-horizontal state and the horizontal state along axial distances.
(The cross-section of pressure distribution difference along axial position z=40~70mm and the cross-section temperature distribution difference along axial position z=140~200mm. θ=30°)



Z α	-90°	-60°	-45°	-30°	30°	45°	60°	90°
40								
50								
60								
70								
140								
160								
180								
200								

By changing the pipe's azimuth angle, the difference of cross-section pressure distribution is vector-dependence that is caused by the component direction of gravity. Compared with the horizontal flow, the differences of cross-section temperature distributions are mainly localized. This is because the component force of gravity causes the magnitude of tangential velocity component to change, and the disturbance of vortex becomes more complex, resulted the change of flow field cannot be uniform.

3.2 Effect of Re on heat transfer and pressure loss

From the observation of Fig. 6, the amplitude of Nu increases linearly due to the increase of Re prompted the swirl intensity. While, the vortex disturbance conditions become significant with the increased Re, thus influence the strength of the heat transfer according to different α. At different α, due to the different axial component of gravity on the flow, the contact time with the heat exchange surface is different that cause the heat transfer time is slightly shorter with gravity assistance. This indicated the heat transfer condition against gravity is better than that of horizontal flow, whereas, when the flow is in same direction with the axial gravity component, the heat transfer condition is weaker than horizontal flow.

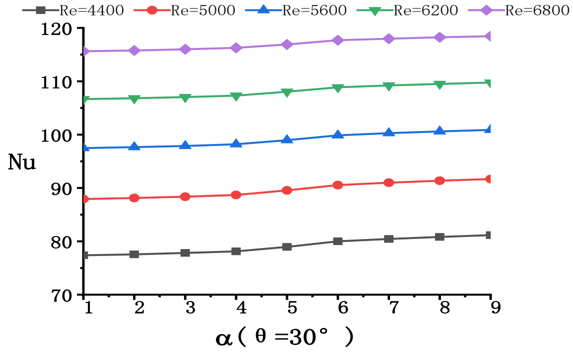


Fig. 6 Variation of Nu with α under the effect of Re

Friction factor (f) decreases as the Re increase and the results are shown in Fig 7. Also, the magnitude of the friction factor reduces with α increase. According to different α, the actual contribution of Re to pressure drop are also different. This is because the magnitude of gravity is mainly caused by the magnitude of the axial component of gravity that either enhance or diminish the contribution of Re. Thus, the friction factor also corresponds to different α.

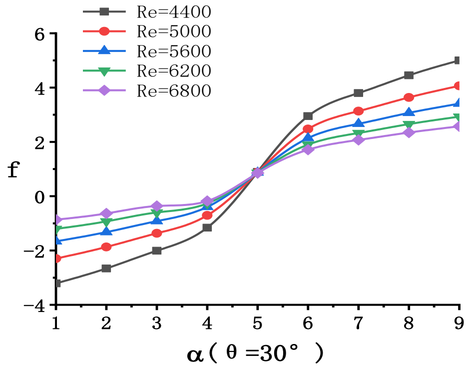


Fig. 7 Variation of f with α under the effect of Re

3.3 Effect of vane angles on heat transfer and pressure drop

From Fig. 8, as the θ increases, the Nu tends to decrease and the amplitude is drastically decrease as well. This phenomenon showed that the water flow through a 30 ° swirler, the rotating pathway is longer than the other two angles and swirl intensity is larger that contributes higher heat transfer effect.

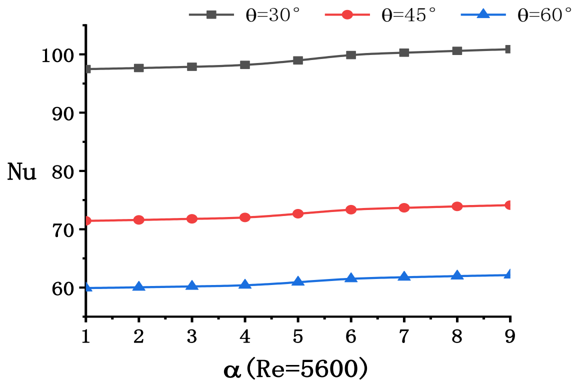


Fig. 8 Variation of Nu with α under the effect of θ

As shown in Fig. 9, when θ = 30° , the friction factor value is low ranging from 1<α<4 compared to other vane angles, however, the friction factor value is high ranging from 5<α<9 compared to other vane angles. This is due to the friction factor often depends on the variation of pressure drop in the flow process. The swirling intensity is diminished when the flow is against the gravity. This is because the rotating pathway is in dominance that caused high pressure drop when θ is small. Whereas the swirling intensity is elevated when the flow is aligned with gravity. This is due to the swirling intensity surpasses the rotating pathway when θ is small that caused relatively low pressure drop.

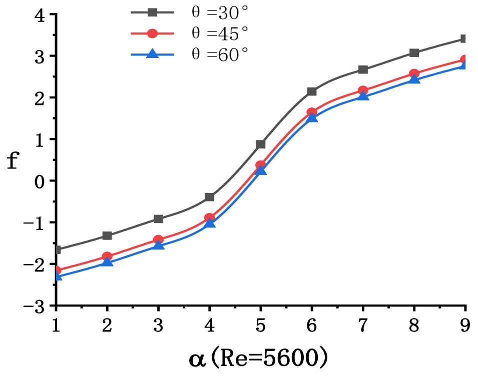


Fig. 9 Variation of f with α under the effect of θ

3.4 Comprehensive evaluation of system heat transfer

In the case of the same pumping power, a comprehensive evaluation of the heat transfer effect of a flow system and the degree of pressure drop can better evaluate and measure the heat transfer performance of a flow system[17].

It can be obtained from Fig. 10, the η value decreases when the flow is against the gravity with the increase of Re. It indicated that the heat transfer performance of the swirling is approaching that of the horizontal flow at a certain rate. The η value increase as α increases ranging from 1<α<4 and 5<α<9 except α=5.

As shown in Fig. 11, as θ increases, the η value decreases accordingly. Furthermore, as α increases ranging from 5<α<9, the η value decreases with θ increase due to the flow is against gravity. Hence, when the flow is aligned with gravity, the heat exchange performance is better than that of the flow against gravity.

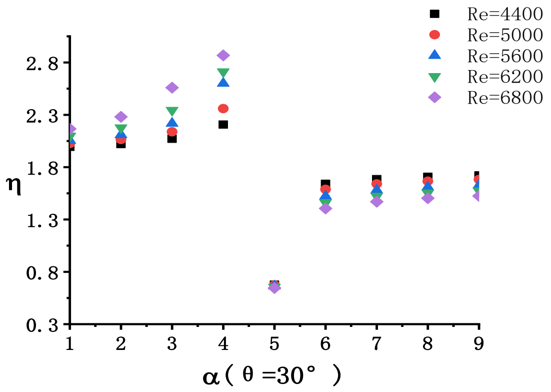


Fig. 10 Variation of η with α under the effect of Re

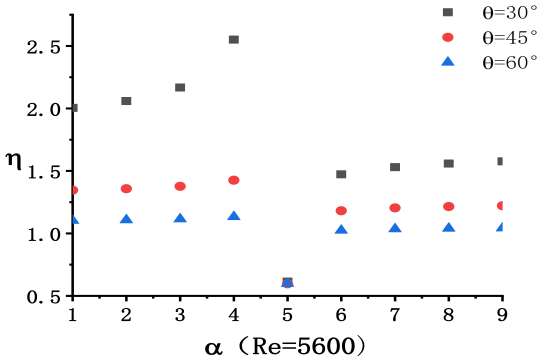


Fig. 11 Variation of η with α under the effect of θ

4. Conclusion

In this paper, the heat transfer, pressure drop and comprehensive heat transfer performance in the swirling tube are studied by three-dimensional numerical simulation under different Reynolds number, vane angle and Pipeline's azimuth angle. The following conclusions can be made:

a) The component force of gravity in the axial direction plays a key role in the heat transfer intensity and pressure drop.
b) Compared with the horizontal flow, the cross-section temperature distribution of the non-horizontal flow changes significantly, and the pressure distribution changes moderately.

c) Compared with Reynolds number, vane angle has a significant influence on the heat transfer and pressure drop characteristics in the swirling tube.

d) The comprehensive heat transfer performance under gravity assisting condition is better than that of against gravity condition. The optimal configuration is under the gravity assistance, vane angle of 30° and the Reynolds number is 6800.

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