A numerical study on the influence of gas-liquid two phase flow on the rotary pump performances

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Abstract. Rotary pump can be used in many fields because of its strong self-priming ability. Many factors may cause the medium in rotary pump system containing gas-liquid two phase. And the suction capacity of rotary pump will decrease sharply in these situations. To study the internal flow mechanism of rotary pump when transporting medium containing gas, the gas-liquid two phase flow in the rotary pump system has been simulated using VOF model under different gas fractions. And the interaction between rotary pump and the pipeline has been considered. The simulation results coincide well with the theoretical calculation results, and the distribution of the flow field match well with the Mandhane flow pattern map. The main conclusions are as follows: with the increase of gas fraction, the flow pattern in the pipeline has the following evolutionary trend (bubble – plug – slug – wavy), and the suction capacity of the pump will decrease. It is mainly because gas medium can fill the partial vacuum produced by the rotor motion easily and is easier to have backflow.

1. Introduction
Rotary pump has strong self-priming ability and gas-liquid mixing transport ability. It can be used in many fields, such as oil discharge of railway tank car, vacuum discharge of sewage, transport of aviation kerosene, and so on. In these practical applications, many situations such as pipeline leak, volatilization of liquid medium, evolution of dissolved gas, can cause the medium containing gas-liquid two phase. The suction capacity of rotary pump will decrease sharply when the medium containing gas. It is mainly reflected as longer transport time and more power consumption [1-3].

Current study on the influence of gas-liquid two phase flow on the performance of rotary pumps mainly stayed in phenomenon describing and fault diagnosis, while less attention has been paid to its internal flow mechanism. However, understanding the distribution of gas-liquid two phase flow in rotary pump and its pipe line has important guiding significance on improving pump and system. Numerical simulation is an effective method in this study.
In this paper, the interaction between rotary pump and the pipeline has been considered. The evolution of the gas-liquid two phase flow pattern in pipeline has been simulated using VOF model. And the change of the rotary pump performance under different gas fraction has been analyzed.

2. Calculation model

2.1. Basic assumptions
Gas-liquid two phase flow is affected by many factors, the situation is complex. In order to simulate this situation effectively, a simplified physical model should be used. The following basic assumptions are put forward: 1) Ignore the influence of the wall to the flow field; 2) In this paper, the inlet pressure and outlet pressure are both normal atmosphere. So the compressibility of the gas medium can be ignored; 3) Ignore the interphase mass transfer and heat transfer.

2.2. Model parameter and mesh generation
Cycloidal rotary pump with three lobes has been used in this calculation. In order to observe the evolution of the gas-liquid two phase flow pattern in pipeline, the pipeline should be long enough, especially the upstream pipeline, as shown in figure 1.

![Diagram of the physical model.](image)

The main parameters of the rotor are: outside radius $R = 72.9 \text{mm}$, rotor center distance $a = 109.5 \text{mm}$. The clearance between the rotor and the pump body is $0.1 \text{mm}$, and between the rotors is $0.2 \text{mm}$, which can fit the values range $0.17 \sim 0.44 \text{mm}$ in normal design [4].

The length of the pipeline is an important parameter when simulating the gas-liquid two phase flow pattern. In related literatures, the length of the pipeline ranging from several meters to tens of meters. Observe the results of their calculation, the flow pattern tends to be stable after a distance. Thus, too long pipeline is unnecessary. After comprehensive consideration, reasonable length of the pipeline should be greater than the pipe diameter of 20 times [5]. The main parameters of the pipeline are: diameter $D = 50 \text{mm}$, length of upstream pipeline $L_1 = 1125 \text{mm}$, length of downstream pipeline $L_2 = 250 \text{mm}$.

The mesh generation result of this model is shown in figure 2. Using unstructured grids in pump area and structured grid in pipeline area. The number of grids in pump area is 386827, in pipeline area is 1617728.
2.3. Numerical method and boundary conditions

Use pressure inlet and pressure outlet as boundary conditions. The rotate speed of the rotors is set to a fixed value \( 600 \text{ r/min} \) using UDF function. Other boundary conditions are set to be wall. Under these conditions, the flow field is completely driven by the rotation of the rotors, and can match reality more exactly.

Turbulence model use standard \( k-\varepsilon \) model. Multiphase model use VOF (Volume of Fluid) model. This model can capture the phase interface effectively [6]. The gas medium is air and liquid medium is water. Study the characteristics of flow field under different gas fractions.

3. Results and analysis

3.1. Validation of the simulation

Firstly, calculation has been done under pure liquid phase condition. Monitor the mass flow rate at inlet. Convert the value to volume flow rate, and the result is \( 0.140 \text{ m}^3/\text{s} \). Do theoretical calculation to validate the result using the equation below:

\[
Q = 2n\lambda \pi R^2 L
\]  

(1)

In this equation: \( Q \) - flow rate, \( \text{m}^3/\text{s} \); \( n \) - rotate speed, \( 600 \text{ r/min} \); \( L \) - width of the rotor, in fluent 2-D simulation, width defaults to 1000mm; \( R \) - outside radius of the rotor, 78.9mm; \( \lambda \) - area usage factor of the rotor, to cycloidal rotary pump, this value only related to the number of lobes, in this case, \( \lambda = 0.406 \) [7].

Put the parameters into equation (1), calculate the volume flow rate is \( 0.136 \text{ m}^3/\text{s} \). Compared with the numerical calculation result, the relative error is 2.94%. Numerical results are reliable.

3.2. Flow pattern analysis

Mandhane had summed up a flow pattern map for gas-liquid two-phase flow in horizontal pipes by observing 5935 flow pattern experiments. In this map, flow pattern has been divided into the following six types: bubble, plug, slug, stratified, wavy and annular. [8, 9].

To compare the simulation results with the Mandhane flow pattern map, the mass flow rate of each phase at inlet has been monitored and converted to corresponding superficial velocity using the equation blow:
\[ J = \frac{Q_m}{\rho A} \]  

(2)

In this equation: \( J \) - superficial velocity, \( m/s \); \( Q_m \) - mass flow rate, \( kg/s \); \( \rho \) - density, \( kg/m^3 \); \( A \) - cross-sectional area of the pipeline, to 2-D simulation, \( A = 2RL, m^2 \).

The superficial velocity of gas and liquid phase under different gas fraction calculated by equation (2) is shown in figure 3 (a), and the operating points have been marked on Mandhane flow pattern map, shown in figure 3 (b).

**Figure.3** Superficial velocity of gas and liquid phase under different gas fraction.

The figures show that with the increase of gas fraction, the superficial velocity of gas phase increase and of liquid phase decrease. And the flow pattern would evolve from plug flow into slug flow. The screenshots of phase distribution under different gas fraction from numerical calculation
results are shown in figure 4.

\[ \text{Figure 4} \] Phase distribution under different gas fraction (numerical calculation results).

As shown in figure 4, the flow pattern in upstream pipeline is bubble flow when the gas fraction is 0.2. The horizontal movement of the flow would be resisted by the rotor when the medium flows into the pump. That would lead to the bubbles coalesce to grow in the blade root position. And big bubbles would be pushed into the downstream pipeline, make the flow pattern develop into plug flow. When the gas fraction is 0.4, the flow pattern in upstream pipeline is plug flow, bubbles coalesce in the pump and make the flow pattern in downstream pipeline have trend to develop into slug flow; With the gas fraction further increase, the above phenomenon is more obvious; When the gas fraction is 0.8, a large proportion of the pipeline space is filled with gas phase, and liquid phase mainly deposited at the bottom of the pipeline. A small amount of liquid is carried away by gas in droplets form. The flow pattern is wavy flow. When the medium flows into the pump, liquid phase is mainly transported by the rotor downside, and the rotor upside almost completely runs in the gas phase.

The simulation results coincide well with the Mandhane flow pattern map. Although a little differences occurred when the gas fraction is 0.8, which is may caused by the model simplification and superficial velocity calculation error, the overall trend is consistent. That is with the increase of gas fraction, the flow pattern in horizontal pipeline has the following evolutionary trend: bubble flow - plug flow - slug flow - wavy flow.

3.3. Pump suction capacity analysis

Vacuum is an important indicator of the pump performance, so the pressure at the inlet of the pump has been monitored. The monitor point is positioned at the border of the upstream pipeline and the pump (0.1mm towards the pump side in x direction). The gas fraction-suction vacuum (maximum) curve is shown in figure 5 (a). The volume flow rate of mixture and liquid medium has been monitored, too. Shown in figure 5 (b).
As shown in figure 5 (a), the suction vacuum is 84.6KPa when the medium is pure liquid phase. The suction vacuum decreased sharply when gas phase enter the medium and only left 4.8KPa when the gas fraction is 0.8. The gradient of suction vacuum decreased with the increase of the gas fraction.

As shown in figure 5 (b), with the increase of gas fraction, the total volume flow rate of the pump decreased. That means backflow exists between outlet and inlet of the pump. As the liquid phase have a lower proportion in the medium, the flow rate of liquid phase decreased faster.

Analyze the reason of the decrease of the pump suction capacity with increased gas fraction as follows: 1) The suction vacuum of rotary pump is produced by the motion of the rotors, and gas medium can fill the partial vacuum easier than liquid medium. From the analysis in 3.2, the partial vacuum area is almost completely in the gas phase when the gas fraction is high. In this situation,
further increased gas fraction would have little influence on the suction vacuum, and the gradient of suction vacuum would decrease. 2) Viscosity of gas is much smaller than liquid. So gas medium is easier to backflow from outlet to inlet, and that would lead to lower volumetric efficiency.

4. Conclusion
In this paper, the gas-liquid two phase flow in the rotary pump system has been simulated using VOF model. The interaction between rotary pump and the pipeline has been considered. The simulation results coincide well with the theoretical calculation results, and the distribution of the flow field match well with the Mandhane flow pattern map. The simulation result is reliable. Based on that, the development of the flow pattern has been analyzed and the reason why pump suction ability would decrease when the medium containing gas has been discussed. The main conclusions are as follows:

1) With the increase of gas fraction, the flow pattern in horizontal pipeline has the following evolutionary trend: bubble flow-plug flow – slug flow - wavy flow. Actual situation with phase change would have some different with this trend.

2) With the increase of gas fraction, the suction ability and transport ability especially liquid medium conveying capacity of the pump would decrease. It is mainly because gas medium can fill the partial vacuum produced by the rotor motion easily and is easier to have backflow than liquid phase.

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