

CFD simulation of degas process in medium consistency pump and experiment

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Abstract. The principal of this work is to simulate the degas process and study experimental performance of medium consistency pump. Based on the actual running performance of the MC pulp pumps, the gas-liquid two-phase flow in the pulp pump was numerically simulated, adopting the Eulerian gas-liquid two-phase flow model and the RNG $k-\varepsilon$ turbulence model. The gas-liquid separation and the gas exhausting process were verified based on the gas-liquid distribution inside the turbulence generator and the pump impeller. The impacts of the standpipe liquid level and the vacuum degree of the vacuum pump to the gas discharging effects were studied. The optimal standpipe liquid level, 5.5m, the critical standpipe liquid level, 3.8m, and the critical degree of the vacuum pump, 0.2atm, were defined and obtained from the simulation. Two methods were presented both enhance the gas discharging effect and decrease the flow loss from the suction hole of the MC pulp pump. A sonar flowmeter and monitoring system is used to experimental set up, and the performance characteristics of MC pump in different conditions were studied. The dimensionless analysis is applied to pulp pumping. The experimental results show that with vacuum degree increasing pump head increased and gas fraction decreased at pump outlet, and the maximum flow rate increases.

1. Introduction

The medium consistency (MC) pulp suspension is a three-phase fluid which contains water, pulp and gas. With the increase of the pulp mass consistency, the gas of fraction in the pulp also increases significantly. For example, when the mass consistency is 15%, the gas volume fraction can reach to 30~40% [1, 2]. In the transportation process of the MC pulp, if the gas can't be discharged in time, the gas would block the pump inlet, which would seriously influence the pump performance. Therefore, the degassing device directly affects the transmission capacity of the MC pulp pumps.

Cao S L [3] (1998) conducted an experimental research on a MC pulp pump, which contained a vacuum pump inside. He founded that the performance of the pump was mainly decided by the vacuum degree. With the increase of the pulp consistency, the gas fraction also increased, which required higher vacuum degree, as also in [4- 5]. A new MC pulp pump was developed and tested by LI H [6] (2008), which achieved expected performance. But the degassing process inside the pump was difficult to measure in details because of the limited experimental condition.

As a low cost and high efficient research method, the numerical simulation has been applied widely to study the gas-liquid two-phase fluid in the centrifugal pumps [7-11]. Frurya [12] (1985) proposed a one-dimensional



incompressible two fluid model which was applied by Kalvin, Noghrehkar and other scholars later. Nishiyama [13] (1989) presented a two-dimensional incompressible two fluid model, and later some scholars, such as Minemura and Uchiyama[14-15], put forward a three-dimensional method based on the single bubble flow model. Minemura [14] (1993) analyzed the two-phase flow in a centrifugal impeller, with the bubbly flow double fluid model and 3D FEM simulation. The result indicated that the model was only applicable to the simulation with the low gas void fraction. Therefore, a fixed cavitation bubble flow model was put forward, but the result was not ideal, which needed to be further improved [15]. Based on the Frurya's model, further considering the fluid viscosity and the gas compressibility, Minemura [16] (1998) carried out a simulation calculation for a low specific speed centrifugal two-phase flow pump, with the simulation results consistent with the experimental data well. Wu Yulin [17] et al (1998) simulated the gas-liquid two phase flow inside the pump impeller using the two fluid turbulence model, but each phase of gas-liquid phase needed to be analyzed respectively in order to get the specific distribution of the pressure and the velocity in the pump impeller.

Due to the lack of the mathematical model for the medium consistency pulp, the gas-liquid-solid three-phase fluid of the pulp suspension was simplified as a quasi gas-liquid two-phase fluid in order to analyze the flow in the MC pulp pumps, with some modification added to the turbulence model. CHEN [18] (2006) simulated the three dimensional turbulence flow field of MC pulp suspension based on CFD technique and optimized the structure of the turbulence generator according to the simulating results. The Eulerian gas-liquid two-phase flow model and the RNG $k-\varepsilon$ turbulence model were used in the simulation. LI [19] (2007) simulated the 2-phase 3-D turbulence flow of the pulp fiber suspension in the hydraulic channel of a low consistency pulp pump. The pseudo-fluid model and the $k-\varepsilon$ turbulence model were modified.

This paper simulated the gas-liquid two phase flow field inside the MC pulp pump, predicting the gas-liquid distribution, analyzing the gas exhaust process, which gives way to enhance the degassing effect of the pump. The experimental performances of MC pump in different conditions were studied.

2. Degas process of the MC pump

The structure of the MC pulp pump with a turbulence generator is shown in figure 1. The figure 2 shows the diagram of the MC pulp pump system. As shown in figure 1, the Turbulence generator and the pump impeller are installed coaxially, located at the pump inlet. The turbulence generator can not only fluidize the pulp suspension, but also separate the gas out of the suspension, and put the gas aggregate around the hub of the turbulence generator. The air mass is formed, going through the suction holes in the pump impeller to the back of the pump impeller. Because of further function of the pump blades, the air mass, including a small amount of water and pulp fiber, reaches the vacuum chamber behind the impeller. The vacuum chamber connected with the vacuum pump through the suction hole, and finally, the gas is discharged out of the MC pump by the vacuum pump.

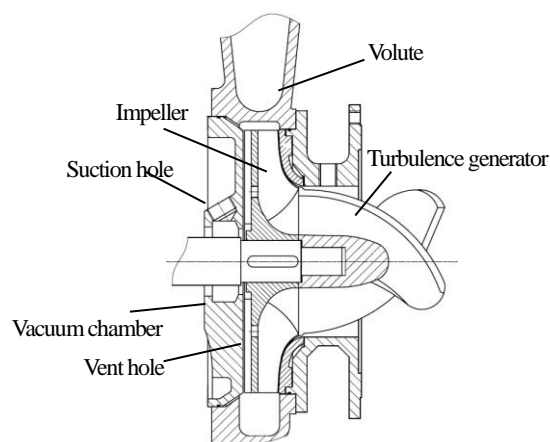


Figure 1. Structure of the MC pulp pump

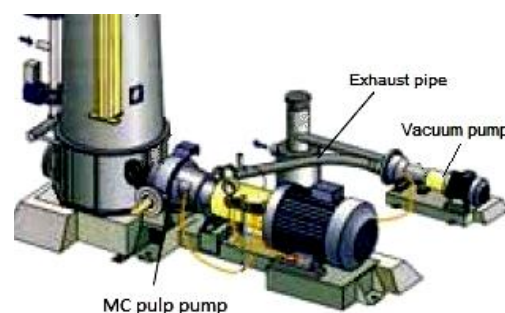


Figure 2. Diagram of the MC pulp pump system

In the degas process, the turbulence generator and the impeller separate the gas from the pulp suspension, and push the gas into the vacuum chamber, with the further action of the vacuum pump, discharging the gas out of the

pump. The hydraulic structure and the size of the turbulence generator and the impeller directly affect the effect of the gas-liquid separation. The vacuum degree of the vacuum pump directly affects the effect of the gas discharge. If the vacuum degree of the vacuum pump is too high, not only can the exhaust gas be sucked, but also the water and the pulp fibers in the pulp suspension can be drawn. If the vacuum degree of the vacuum pump is too low, the degas performance would be inefficient.

3. Hydraulic performance simulation and verification of the MC pump

The operating conditions of the MC pulp pump prototype are as follows: the flow rate is $561\text{m}^3/\text{h}$, the head is 130m, the rotational speed is 1980r/min, the motor power is 362kW, the total efficiency is 54.9%, the unbleached pulp mass concentration is 10%, the gas volume fraction is 10%, the apparent viscosity is $8.42\text{Pa}\cdot\text{s}$, the density in the fluidization area is $1250\text{kg}/\text{m}^3$. The inlet diameter of the pulp pump is 270mm, the outlet diameter is 150mm. There are four components consisting of the simulation region, which are turbulence generator, the impeller, volute, volute and vacuum chamber, as shown in figure 3.

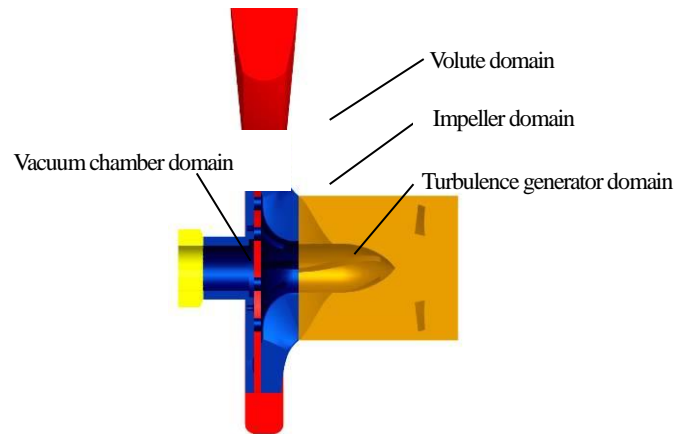


Figure 3. MC pulp pump calculation model

The ANSYS 15.0 CFX is applied to the calculation, setting the velocity inlet and the pressure outlet as the boundary conditions. Mesh independency was checked shown in table 1 by demonstrating that additional cell number did not change the head by more than 2% comparing to the fine cell number. Compared to fine cell, deviations H is 2.03% for coarse cell, and there is only 1.24% for medium cell. The numbers of mesh with three-dimensional mesh of centrifugal pump is 1515675, shown in figure 4.

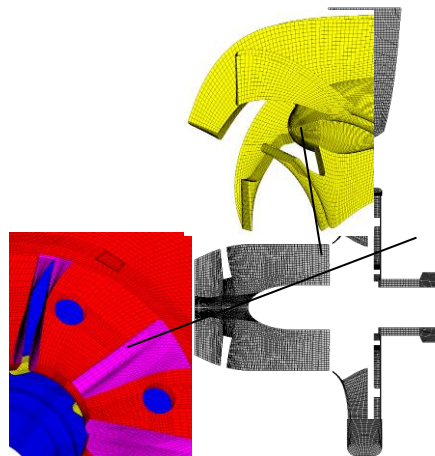


Figure 4. Structure mesh

Table 1. Mesh independency investigation

Cell number	Inlet extension	Turbulence generator	Impeller
coarse	1.25×10^5	2.56×10^5	4.51×10^5
medium	2.02×10^5	4.23×10^5	3.78×10^5
fine	2.48×10^5	7.89×10^5	5.02×10^5

Volute	Exhaust pipe	H/m	Deviation of $H/\%$
2.33×10^5	1.29×10^5	133.21	2.03
3.39×10^5	1.73×10^5	132.18	1.24
6.07×10^5	2.34×10^5	130.56	--

The Eulerian two-phase turbulence model is used, and the RNG $k-\varepsilon$ turbulence model is adopted. Compared with the actual operating performance, the simulation performance of the MC pulp pump is shown in table 1. As shown in table 2, the errors between the simulation results and the actual running conditions are less than 10.85%, which is caused by the simplification and approximation of the gas-liquid-solid three-phase flow of the pulp suspension to the quasi gas-liquid two-phase flow. Furthermore, the gas volume fraction of the two-phase flow is too large and the two-phase flow in the pump is too complex to simulating the flow precisely. However, the simulation results can reflect the internal flow field of the MC pulp pump, especially providing a numerical simulation method for the study on the gas-liquid separation of the MC pulp pump.

Table 2. Pump performance by the simulation and from the actual operation

	Actual operation	Simulation	Errors%
Heads (m)	130	132.18	7.27
Powers (kW)	362	322.7	10.85
Efficiencies (%)	61	55.7	8.69

4. Degas process simulation of the MC pump

4.1 Boundary conditions

In order to simulate the gas exhaust process, the suction hole is defined as a gas outlet in the simulation. From table 2, the simulation pump head is 140.5m. Considering the liquid level H of the standpipe is 10m, as shown in figure 4, the pump outlet pressure value is set to 15atm. The exhaust pipe of the pump is connected to the degassing vacuum pump. At first, the vacuum degree of the exhaust port is set to 0, namely the vacuum pump doesn't work, so the pressure at the gas outlet is 1 atm. The numerical simulation is also conducted with CFX. The settings of the other boundary conditions and the models of the numerical simulation are the same as those above.

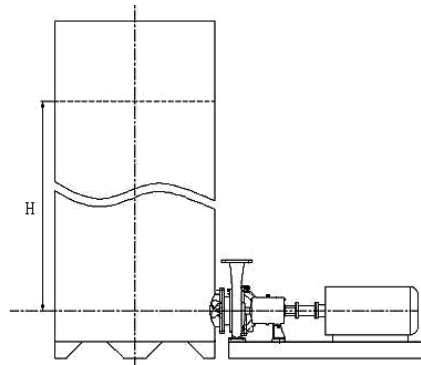


Figure 5. Standpipe diagram of the MC pulp pump

4.2 Simulation results

The pump rotor is composed by the turbulence generator and the pump impeller. The gas phase distribution and the pressure distribution on the surfaces of the pump rotor and the pump back impeller obtained by simulations are shown in figure 5 and figure 6, respectively.

From figure 5 and figure 6, we can find that the large area of low pressure appears around the hub of the pump impeller and the hub of the turbulence generator, extending to the outlet of the pump impeller. At the same time, the air masses appear in those low pressure areas, with the gas volume fraction amounting to 99.9%. The phenomena demonstrate that the air masses gather in the pump low pressure area, and the air masses can move to the holes in the impeller. On the surface of the impeller back, the cricoid low pressure zone forms near the axis, as shown in figure 5, corresponding with the air masses gathering area, as shown in figure 6. Because of the existence of the volute cutwater of the pump, the gas phase distribution on the surface of the impeller back is uneven, as shown in figure 6, but it can still explain that the air masses in the pump impeller are exhausted from the holes, which verifies the degas process of the MC pulp pump.

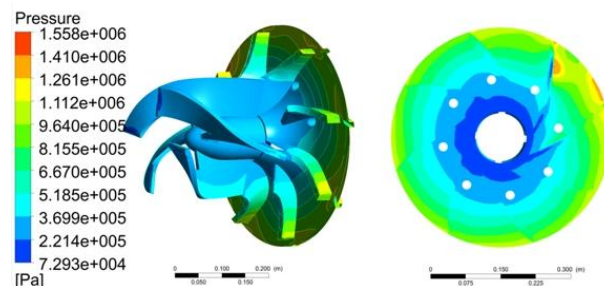


Figure 6. Pressure distribution on the surface of the rotor (L) and impeller back (R)

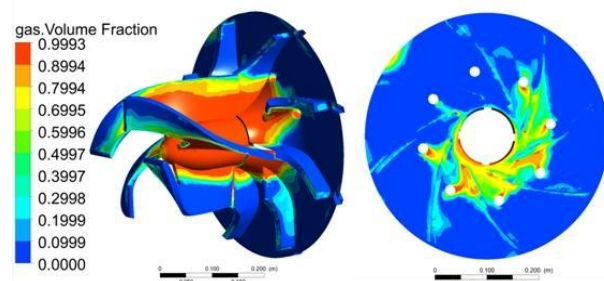


Figure 7. Gas distribution on the surface of the rotor (L) and impeller back (R)

In order to show the exhaust process and effect in the MC pulp pump, the section gas void fraction, the gas volume fraction and the gas mass flow rate at different sections, such as Section A, the pump inlet, Section B, the turbulence generator inlet, Section C, the pump impeller inlet, Section D, the pump outlet, and the section E, the pump suction hole, shown in figure 3, are listed in table 3.

Table 3. Gas contents at different sections

Section s	Section gas void fractions (%)	Gas volume fractions (%)	Gas mass flow rate (g/s)
A	10	10	18.427
B	4.698	13.0709	18.340
C	36.196	3.4	19.229
D	0.049	0.129	0.0632
E	83.521	81.69	17.757

From table 3, we can find that both the section gas void fraction and the gas volume fraction at the pump suction hole section E have reached more than 80%, and the gas mass flow rate at Section E is 17.757g/s. Both the section gas void fraction and the gas volume fraction at the pump outlet section D decrease to 0.049% and 0.129% respectively, and the gas mass flow at the pump outlet section D falls to 0.0632g/s. This demonstrates that the gas exhaust device can discharge the air out of the pump effectively, showing that the MC pulp pump with the turbulence generator can transport the MC pulp with high gas void fraction.

5. Method to improve the degas effect

The liquid level of the standpipe can influence the pressure at the pump inlet, and the vacuum degree of the vacuum pump can change the pressure at the pump suction hole, which both will greatly impact on the pump gas exhausting.

5.1 Influence by the standpipe liquid level

When the pressure of the pump suction hole was set to 1atm, namely no vacuum pump connected the pump, the exhaust performances of the pulp pump under different standpipe liquid levels are shown in figure 7, where Q_m refers to the water flow rate at the pump exhaust outlet, φ_1 is the gas volume fraction at the pump outlet, and φ_2 is the gas volume fraction at the pump suction hole.

With the increase of the standpipe liquid level, the water flow rate at the pump exhaust outlet Q_m increases greatly, while the gas volume fraction at the same outlet, φ_2 , improving significantly, then reducing gradually. The gas volume fraction at the pump outlet, φ_1 , reducing greatly, then slightly. It means higher standpipe liquid level will bring more water loss and lower gas volume fraction at the pump exhaust outlet, which will not benefit to the pump efficiency and degassing effect. From figure 7, when the standpipe liquid level is 5.5m, the water flow rate Q_m is 0.0947 kg/s, and the gas volume fraction at the suction hole, φ_2 , reaches 98.67%, the gas volume fraction at the pump outlet, φ_1 , is less than 0.1%. The standpipe liquid level in this situation is defined as optimal standpipe liquid level.

Based on the numerical simulation, when the liquid level is set to 3.8m, no water or gas flows out from the pump suction hole, while gas volume fraction at the pump outlet is relatively high. The liquid level in this situation is defined as the critical level. If the standpipe liquid level is below the critical level, which results in no gas discharging from the pump exhaust outlet, the vacuum pump should be connected to the pump to improve the exhausting effect.

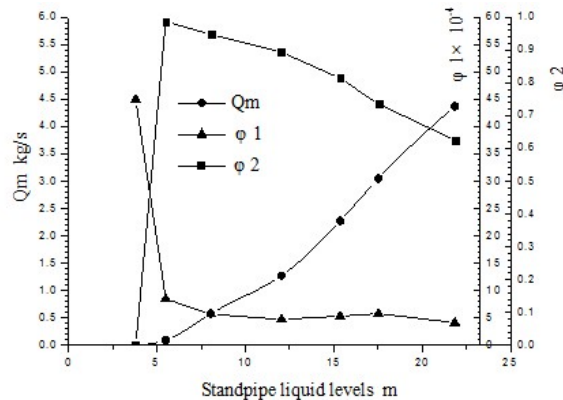


Figure 8. Exhaust performance at different standpipe liquid levels

5.2 Influence by the vacuum degree

When the standpipe liquid level is 3.8m and the vacuum pump isn't equipped with, no water or gas flows through the pump suction hole. Setting different vacuum degrees of the vacuum pump to 0.2atm, 0.4atm, 0.6atm, 0.8atm, respectively, and the standpipe liquid level 3.8m, the performances of the pump exhaust are shown in figure 8.

From the figure 8, when the vacuum degree is 0.2atm, the water flows out of the pump exhaust outlet, with a flow rate only 0.0259kg/s, and the gas volume fraction at the suction hole reaches 99.67%, the gas void fraction at the pump outlet less than 0.1%. This indicates that the vacuum pump can achieve a good exhaust effect. With the increase of the vacuum degree, the gas volume fractions at the pump exhaust outlet, ϕ_2 , decrease slightly, but still higher than 95%. While the water flow rate at the pump exhaust outlet, Q_m , also increased slightly, but still maintaining at a low level. From figure 8, vacuum degree 0.2atm is defined as the critical degree, when the pulp pump has the lowest flow loss and good gas discharging effect. This illustrates that the vacuum degree of the vacuum pump should be set at critical degree when the standpipe liquid level is at the critical level.

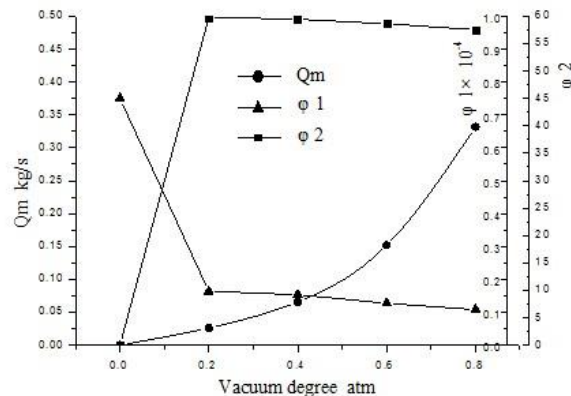


Figure 9. Exhaust performance at different vacuum degrees

From the research above, the methods to improve the pump exhaust effect can be summarized as follows:

- On the premise of meeting the pulp transportation technique requirements, in order to decrease the flow loss at the pump suction hole, the liquid level of the standpipe of the MC pulp pump could be set at optimal standpipe liquid level, with no vacuum pump needed;
- If the liquid level is below the critical level, the degassing vacuum pump should be mounted or the vacuum degree of the existing degassing vacuum pump should be increased, but the vacuum degree of the vacuum pump should be at a low level.

6. Experimental test

Due to the specialty of pulp, External performance of pulp pump is very different with general centrifugal pump, therefore a particular test system was designed in figure 9. The experiment set up consists of a MC pump, a frequency conversion motor, a vacuum pump, a ball valve, a vacuum manometer, a pressure sensor, a sonar flowmeter, a slide valve, and a tank. The MC pump is driven by a 4-pole induction motor, and the speed of induction motor is controlled by an inverter to realize different rotational speed. The vacuum pressure is controlled by ball valve. The pulp flow rate is measured by sonar flowmeter. The pressure signal is acquired by pressure sensor. The parameters of sensor are shown in table 4.

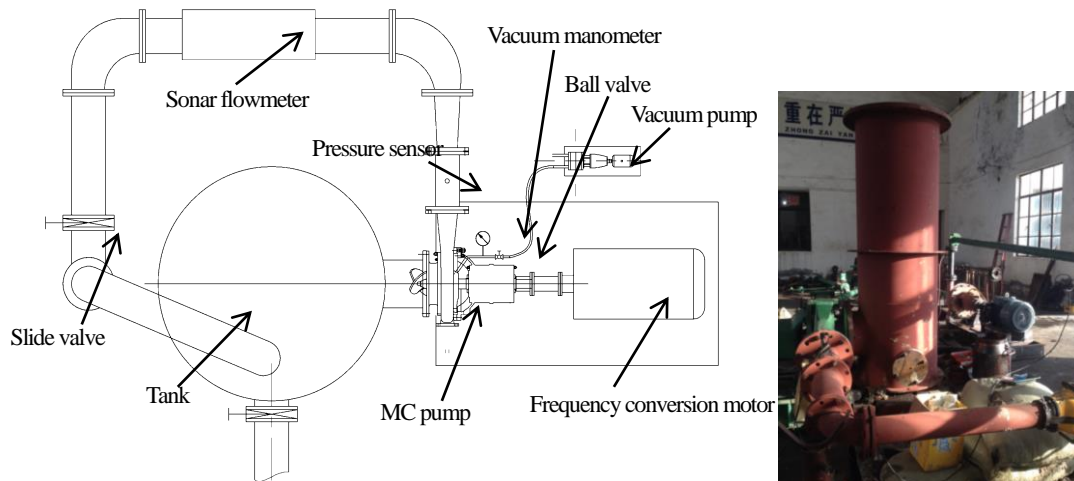


Figure 10. Schematic diagram of testing

Table 4. Sensor parameters

apparatus	Test data	range	Accuracy
Pressure sensor	Pressure at pump outlet	-100~1000kPa	±0.25%
Sonar flowmeter	Pulp flow rate and gas volume	1~10m/s 0~20%	±5%
Vacuum pump	Vacuum pressure	0~-0.1MPa	2.5

The sonar flowmeter, SONARtrac[®]VF/GVF-100, consists of volume flow rate and gas volume fraction shown in figure 10. Comparing with a general electro-magnetic flow meter, the sonar flowmeter does not in direct contact with pulp flow, so the data is prevented from liner inside pipe, fouling impact. The sonar flowmeter is interposed MC pump discharge piping, using sonar measurement principle can be directly measured flow rate and gas rate, and which has no pressure limited, no wear and no signal attenuation characteristics.



Figure 11. Sonar flowmeter

The performance curves of MC pump at different vacuum pressure are shown in figure 11. Some pulp is discharged from vacuum pump at critical vacuum pressure, which results in waste pulp. With vacuum pressure increasing, the head increases and the gas fraction at MC pump outlet decreases. When flow rate is less than $0.4Q_m$,

the head decreases slightly, and with the flow rate continued to increase the gas volume increase, as the result, head decreases sharply. When the vacuum degree is -24 kPa, efficiency is less than that at critical vacuum pressure. The MC pump can work without vacuum condition, but with flow rate increasing performance significantly deteriorates, and head and efficiency drop significantly. From figure 11, as a result of no vacuum large amount of gas blocks impeller passage when pulp concentration is 10%, so MC pump quickly losing transmission capacity. With vacuum pressure increasing, the maximum flow rate increases.

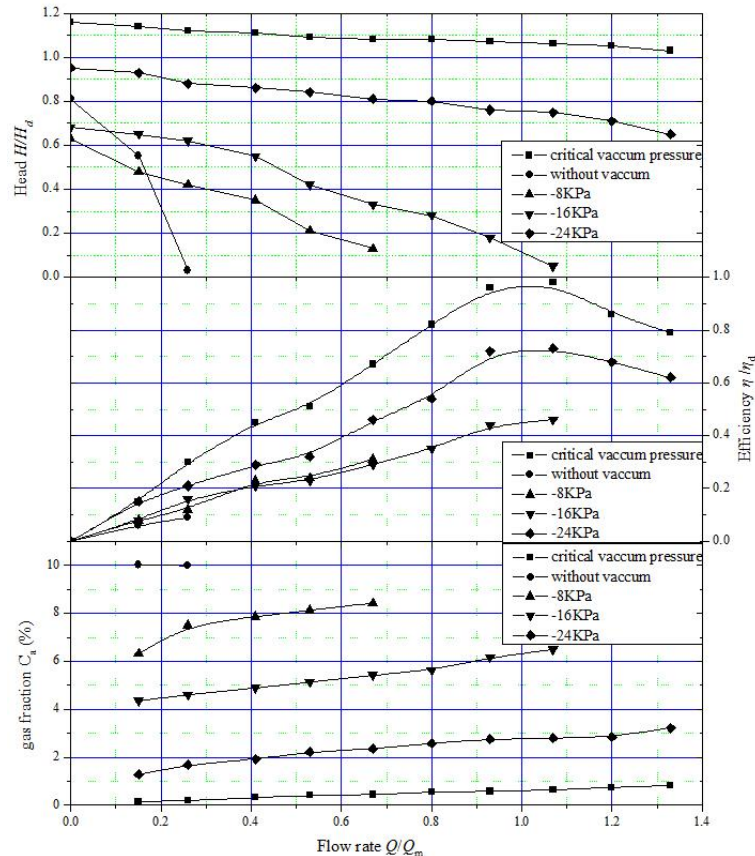


Figure 12. Performance curves of different vacuum pressure ($C_m=10\%$, $n=1980\text{r/min}$)

7. Conclusions

The whole flow field of the MC pulp pump with a turbulence generator is numerically simulated and verified, and analyses of pressure distribution and the gas phase fraction distribution indicated the air masses gathering in the pump low pressure area, moving through the holes in the impeller, and discharging from the pump suction hole. A MC pump experimental set up is built. The operation performance is studied under different conditions.

The standpipe liquid level, with small water flow rate and big gas volume fraction at the suction hole, is defined as optimal standpipe liquid level. The standpipe liquid level is defined as critical standpipe liquid level. 5.5m and 3.8m as optimal and critical standpipe liquid level, respectively. The vacuum degree, with the low flow loss and best gas discharging effect, is defined as the critical degree. 0.2atm is obtained as critical degree in this MC pump system.

There are two ways to improve the exhaust effect. At first, the standpipe liquid level should be lower than optimal standpipe liquid level to decrease the drain water out of the pump. When the liquid level is low below the critical liquid level, then, a vacuum pump, with the vacuum degree set at the critical degree, should be connected to the pump suction hole to increase the degassing effect.

The experimental results show that pump head increases and gas fraction decrease at pump outlet, and the maximum flow rate increases with vacuum degree increasing.

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