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INFLUENCE OF PRESSURE FLUCTUATION ON REFLUX VALVE IN A SELF-PRIMING PUMP WITH OUTER RECIRCULATION

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ABSTRACT

The pressure fluctuation caused by impeller-volute interaction is one of the factors which affect the stability of self-priming pump with outer recirculation. Based on the RNG $k-\varepsilon$ turbulence model, three-dimensional unsteady turbulence flow in a self-priming pump was simulated in this paper. Pressure fluctuations were obtained at 26 monitor points distributed at eight sections of the volute and on the reflux valve, and the influence on the valve was analyzed. The CFD results show that the main frequency of monitor points is blade passing frequency, and the pressure difference between maximum and average is minimal at the fifth section, which is 1.3%~2.4%. Using pressure sensors and LabVIEW system, the pressures at third, fifth and seventh sections were tested. The experimental results show that pressure fluctuation layouts are similar as those from CFD, and the pressure difference at the fifth section is 4%, also the minimum. The position also is found with minimal influence on reflux valve. Reflux hole should be placed at 200° ~ 220° from the tongue along the direction of the impeller rotation. Further, according to the CFD results, the Finite Element Analysis (FEA) of the reflux valve was carried out. FEA shows that the valve can close the reflux hole completely after self-priming process, which gets a good hydraulic performance when the pump runs normally.

NOMENCLATURE

H	pump head
Q	flow rate
Z	blade number
n	rotating speed
ρ	fluid density
C_p	pressure coefficient
D_1	inlet diameter of impeller
D_2	outlet diameter of impeller
b_2	outlet width of impeller
u_2	circumferential speed at impeller outlet
ΔP	value between instantaneous pressure and average pressure
BEP	best efficiency point

INTRODUCTION

Self-priming pumps with outer recirculation are important equipment in irrigation system, whose performance affects the efficiency of irrigation system. After a long time of running, the reflux valve in the self-priming pump with outer recirculation will have many problems, such as instability, fracture. And if the valve cannot close the reflux hole, the fluid will circulate through the reflux hole in the pump housing, which results in a low efficiency of the pump[1-2]. The pressure fluctuations caused by impeller-volute interaction is one of the important factors which affect the stability of the reflux valve. The research about the pressure fluctuations in the pumps can date back to 1980s. Dring et cl.[3]（1982）found two factors affecting the rotor-stator interaction: potential flow and wake flow. Iino[4]（1985）tested the blade pressure fluctuations in a centrifugal pump, which indicated that mass flow and the angle between blade and diffuser were the main factors causing fluctuations. Iino[4]（1985）also used singularity method and RANS model to calculate the unsteady flow caused by impeller-diffuser interaction inside a diffuser pump. Kevin[6]（1999）discovered that pressure fluctuations caused by impeller-volute interaction increased with the mass flow changing from the best efficiency point(BEP) to the larger flow point for a high specific speed pump. Shi[7-8]（1999，2001）simulated the pressure fluctuations of blade downstream in a diffuser pump. After comparing the simulation with the experimental data, he found that the frequency components of the pressure fluctuations in the diffuser passage were comprised mainly of the impeller blade passing frequency and its higher harmonics. He also found that the impeller-diffuser interaction was caused chiefly by potential interaction and wake impingement with the diffuser vanes. Wang[9]（2001）investigated the pressure fluctuations in the diffuser passage, and indicated that the main frequency components appeared in the off-design point which were also consisted of the blade passing frequency and its higher harmonics.

Pressure fluctuations inside a self-priming pump with outer recirculation will influence the stability of the reflux valve. This paper focuses on the influence of the pressure fluctuations on the reflux valve, which is investigated combining with the transient simulations, theoretical analyses and experimental studies.

NUMERICAL CALCULATION MODEL AND METHOD

1.1 Calculation Parameters

Key parameters of the diesel-driven self-priming pump typed 65ZB-40C are as follows:

Flow rate Q: 30m³/h;
Pump head H: 40m;
Rotating speed n: 2900r/min;
Blade number Z: 6;
Inlet diameter of impeller D_1: 65mm;
Outlet diameter of impeller D_2: 185mm;
Outlet width of impeller b_2: 9mm.

Figure 1. illustrates the three-dimensional geometry of self-priming pump with outer recirculation.

1.2 Computational Method and Initial Conditions

In this study, the unsteady turbulence numerical simulations are conducted by Fluent. Unsteady incompressible Reynolds-averaged Navier-Stokes equations are employed to execute the time-accurate calculations associated with true transient impeller-volute interaction in this self-priming pump. The pressure-based, fully conservative, finite volume method is used in the code. The turbulent viscosity is calculated using the RNG $k-\varepsilon$ turbulence model. An implicit first-order scheme is used for the time dependent term. To avoid excessive numerical dissipation, a third-order accurate interpolation scheme (QUICK) is used for the discretization of the convection terms and central difference scheme is used for diffusion terms. The discrete governing equations are solved with the SIMPLE（Semi-Implicit Method for Pressure Linked Equations）algorithm.

Suitable initial conditions are the keys to calculate the unsteady flow accurately[10]. In this paper, we set the steady calculation results as the initial conditions. With grid rotation of each 8 degree, we get a time-step convergence on the solution of the turbulence. Then, the unsteady calculation results consist of convergence solutions at all time. From these unsteady calculation results, the pressure fluctuations changing with time are obtained inside the flow passage. The time step is set as 0.00045977s.

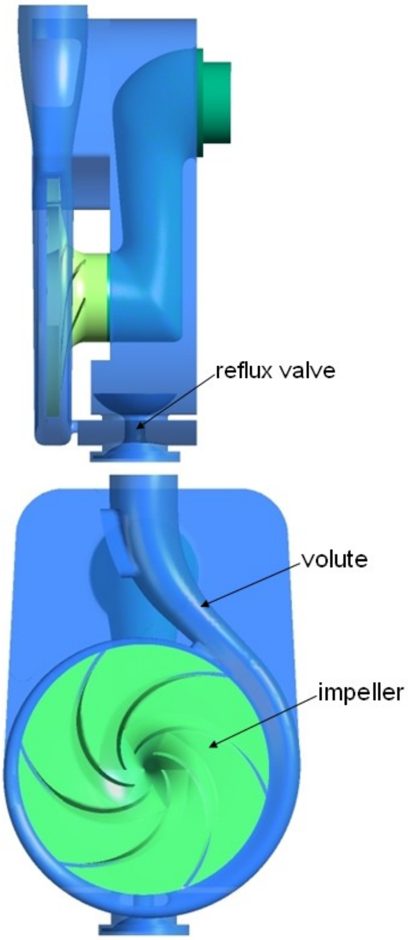


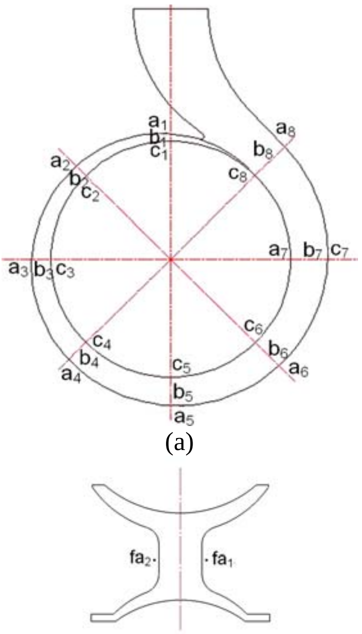
Figure 1. Geometry of Self-priming Pump with Outer Recirculation

1.3 Simulation Schemes

Because we can not judge if the reflux valve closes the hole completely and how the reflux valve influences the flow field inside the self-priming pump, two simulation schemes are carried out:

(1) Reflux valve does not close the reflux hole (Model 1)
(2) Reflux valve closes the reflux hole completely (Model 2)

In order to study the influence of pressure fluctuations on the valve, the pressures at different sections in the volute and on the reflux valve are monitored. Figure 2(a) shows 24 monitor points in the volute, and Figure 2(b) shows 2 monitor points on the reflux valve.



(a)

(b)

Figure 2. Pressure Monitor Points in the Pump

RESULT ANALYSES

2.1 Pump Performance Predictions

At five different flow rates, 0.6*Q*(18m^3/h), 0.8*Q*(24m^3/h), *Q*(30m^3/h), 1.2*Q*(36m^3/h) and 1.4*Q*(42m^3/h), we simulate the pump flow, get the steady results, and compare them with the experimental data. Figure 3. and Figure 4. show the *Q-H* curves and *Q*-Efficiency curves.

Figure 3. and Figure 4. indicate that the tendencies of prediction results are the same as the experimental data, and all the differences are about 5%. At the 0.8*Q*（24 m^3/h）flow rate, the prediction differences of head and efficiency are a little higher than that at the other flow rates by 2%~3%. At the 1.4*Q*（42 m^3/h）flow rate, the prediction differences are the smallest, with the efficiency difference only 2.06%. At the BEP, the prediction differences of head and efficiency are all within 5%. It means this calculation model can predict the pump performance accurately enough for engineering, also can validate further predictive analysis in some extent.

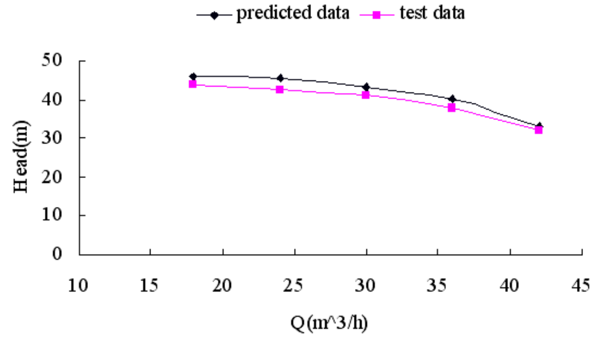


Figure 3. *Q-H* Curves

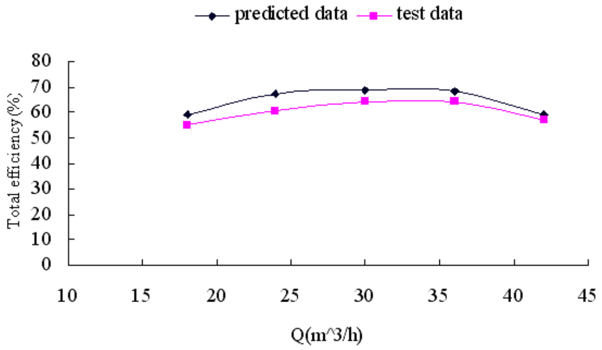


Figure 4. *Q*-Efficiency Curves

2.2 Pressure Fluctuation Simulation Results and Analyses

The shaft frequency of the self-priming pump is 48.33Hz, and the blade passing frequency is 290Hz at the BEP. In order to ensure the accuracy of numerical calculation, all data are obtained after the fifth cycle.

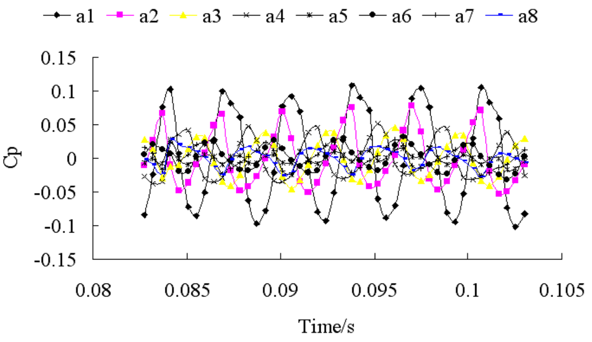
Figure 5. illustrates the time domain chart of eight monitor points at the BEP.

Pressure coefficient is defined by

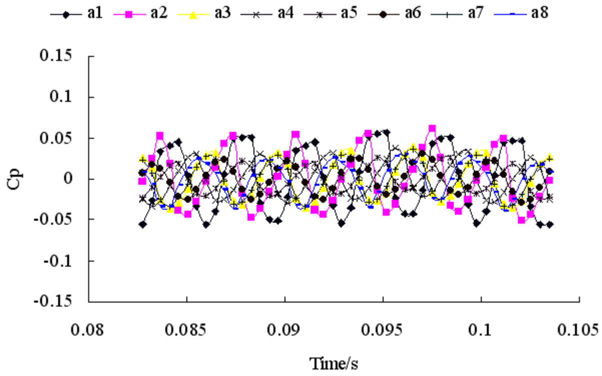
$$C_p = \Delta P/(0.5\rho u_2^2) \tag{1}$$

Where ΔP ——Value between instantaneous pressure and average pressure(Pa)
ρ —— Fluid density(kg/m^3)
u_2 —— Circumferential speed at impeller outlet(m/s)

As shown in Fig.5., all the curves of pressure fluctuations at different monitor points are consistent. At the fifth section of the Model 1, the curve of pressure fluctuations per circle has twelve crests and troughs, but the other curves all have six crests and troughs, the same number as the impeller blade. In the Model 1, the valve is assumed not closed, so the fluid flows through the reflux hole into the volute, reducing the pressure fluctuations. That is the reason why the curve of the fifth section has twice rests and troughs than the others'. The first section and second section in the volute are close to the tongue, so the pressure fluctuations in these areas are much higher than the others'. The flow at the tongue in the Model 1 is complex, and the amplitude of pressure fluctuations is twice higher than that in the Model 2. These indicate that this self-priming pump not only has lower efficiency, but also bigger noise, when the valve is not closed. From the third section to the eighth section, there are no high frequency fluctuations. The pressure difference between maximum and average is 1.3%~2.4%. The fifth section has the minimal pressure fluctuation. So, considering the stability of reflux valve, the reflux hole should be placed nearby the fifth section, 200° ~ 220° from the tongue along the direction of the impeller rotation in practice.



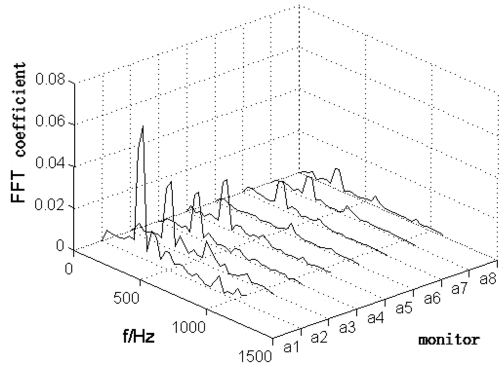
(a) Model 1



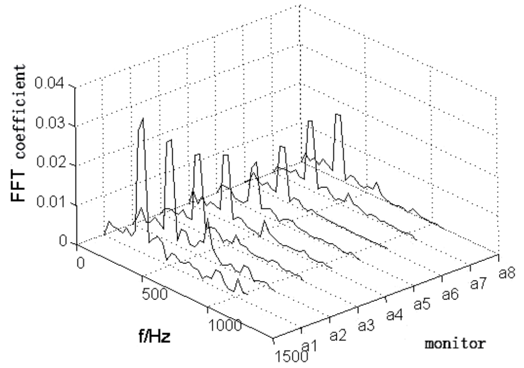
(b) Model 2

Figure 5. Time Domain Charts of Eight Monitor Points at the BEP

As shown in Fig.6., the pressure fluctuations in the fifth section are steady. The main frequency of all monitor points is 305Hz, the same as the blade passing frequency.



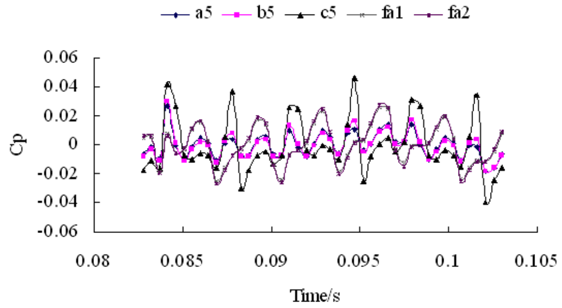
(a) Model 1



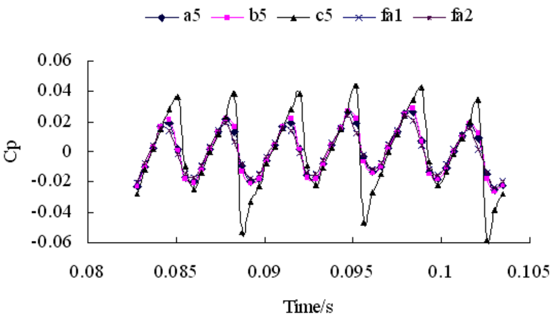
(b) Model 2

Figure 6. Frequency Domain Charts of Eight Monitor Points at the BEP

As shown in Fig.7., five pressure fluctuation curves near the fifth section have twelve peaks and troughs in the Model 1, while they have six peaks and troughs in the Model 2. c_5 is at the rotator-stator interface, so the pressure fluctuation is the maximum. Two pressure fluctuation curves (fa_1 and fa_2) which are nearby the reflux valve are coincident, and the pressure difference between peak and average is 2.4%, a little higher than a_5. Considering the influence of pressure fluctuation, the reflux hole should be placed at the bottom of the volute.



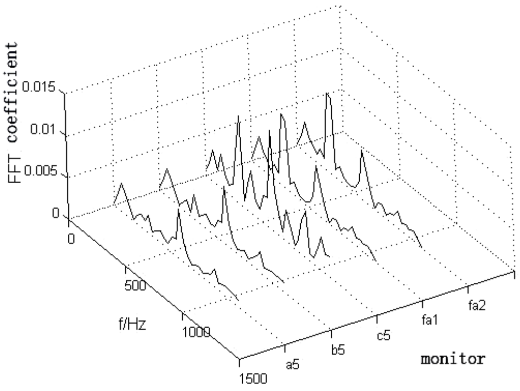
(a) Model 1



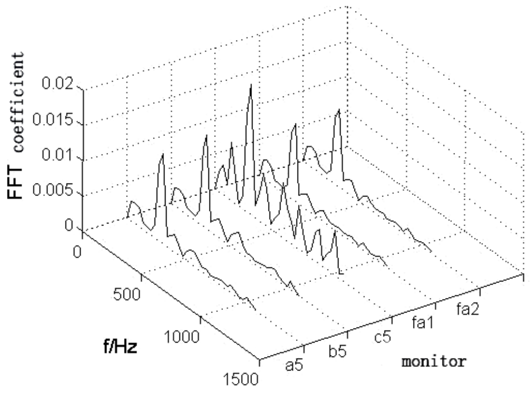
(b) Mode 2

Figure 7. Time Domain Charts of Five Monitor Points at the BEP

As shown in Fig.8., there is no high-frequency pressure fluctuation nearby the reflux valve. The main frequency of all monitor points is also 305Hz, the same as the blade passing frequency.



(a) Model 1



(b) Model 2

Figure 8. Frequency Domain Charts of Five Monitor Points at the BEP

PRESSURE FLUCTUATION EXPERIMENT

3.1 Experimental Equipment and Experiment Steps

This experimental bed is comprised of 65ZB-40C self-priming pump, pipe system, valves, motor, pressure sensors, electronic flow meters and LabVIEW, as shown in Fig.9.

Figure 9. Experimental Equipment

Experiment steps are designed as follows:

(1) Install motor, pump and pipes to build an open pump test bed.

(2) Connect LabVIEW with pressure holes at the third, fifth and seventh section by pressure sensors, and design Data Acquisition System software modules. As shown in Fig.10.

(3) Start the motor. After five minutes running, regulate the valve, then collect the data and record the rpm at the following flow rates: 0.4*Q*(12m^3/h), 0.6*Q*(18m^3/h), 0.8*Q*(24m^3/h), *Q*(30m^3/h), 1.2*Q*(36m^3/h) and 1.4*Q*(42m^3/h). Every collecting lasts 20 seconds.

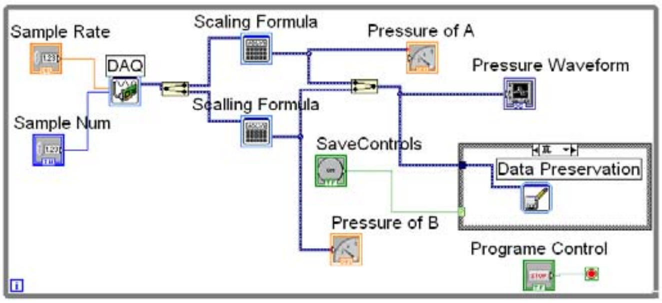


Figure 10. LabVIEW Software Module

3.2 Experimental Data Analyses

As shown in Fig.11., all the pressure fluctuation curves at different sections shape similarly, vary periodically. But the fifth section has a 90-degree phrase difference compared with 3rd and 7th sections, which shows that when the curves of the 3rd and 7th section appear peaks, the 5th section curve appears troughs. The third and seventh sections are closer to tongue, so the pressure fluctuations are higher than that of the fifth section.

The pressure fluctuation at the 5th section is minimal, the same as the simulation results. And the pressure difference between peak and average at the fifth section is 4%, higher by 1.6%~2.7% than that from unsteady numerical calculation.

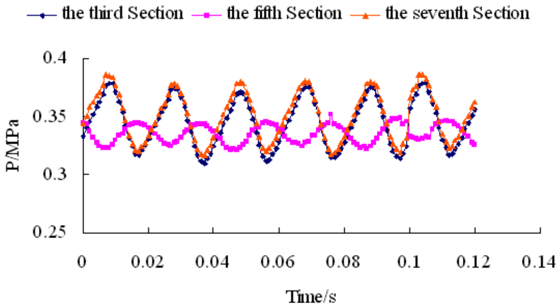


Figure 11. Time Domain Chart of Three Sections at the BEP

As shown in Fig.12., the test frequency is 50Hz, close to the theoretical shaft frequency 48.3Hz, and these are no high pressure fluctuations when the test pump runs normally.

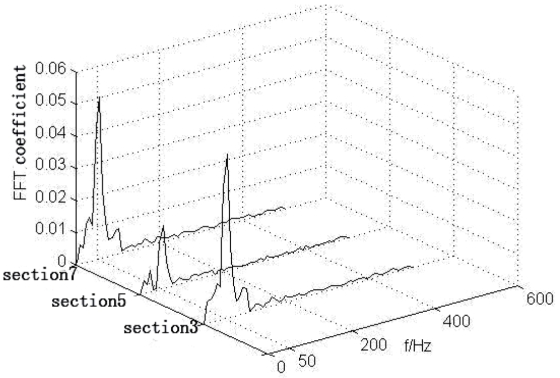


Figure 12. Frequency Domain Chart of Three Sections at the BEP

Because of the limit capacity of the test equipment, the blade passing frequency can not be obtained. But the tendency of pressure fluctuations shows a good agreement with that of unsteady numerical calculations.

FINITE ELEMENT ANALYSES TO THE VALVE

The study above indicates that the pressure fluctuations affect the stability of the valve minimally when the valve is placed at the fifth section. We also know that the state of reflux valve, closed or opened, influences the efficiency of the self-priming pump. What is the state of the valve in running? According to the CFD results above, the Finite Element Analysis (FEA) for the valve is done by ANSYS software. We judge the state of the valve by the deformation of the valve.

4.1 Parameters of the Valve

The radius of the upper surface of the above disk R_1 is 40mm. The radius of the lower surface of the above disk R_2 is 37mm. The radius of the upper surface of the low disk R_3 is 32mm. The radius of the lower surface of the low disk R_4 is 37.5mm. Total height H is 48mm. The diameter of the column a is 15mm. Figure 13 illustrates the reflux valve.

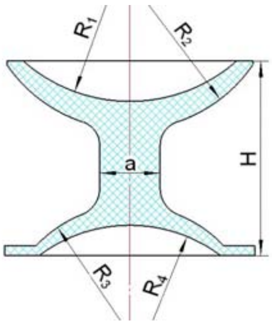


Figure 13. Reflux Valve

The material of the valve is nitrile rubber(NBR), with a hardness 62HS, modulus of elasticity 3.8MPa，Poisson's ratio 0.47, as shown in Fig.14.

Figure 14. Hardness Test

4.2 Loads on the Valve

The foot of the valve is fixed. The lower surface of the low disk is in the atmosphere, so the load on this surface is 0Pa. The lowest pressure, 393587.6Pa, taken from the CFD numerical simulation, loads on the other surfaces.

4.3 FEA Results

Displacement Analyses. As shown in Fig.15., the main deformation of the valve occurs in the low disk. The above disk and column moves along the vertical direction with the low disk deforming. The maximum displacement in the vertical direction is 13.58mm, the red part in Fig.16. The design distance between the lower surface of above disk and seal ring of the actual pump is 9.5mm, which is smaller than the displacement. So the valve can close the reflux hole completely after self-priming according to the FEA results.

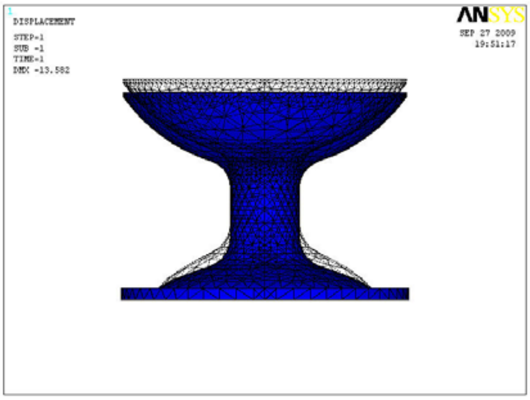


Figure 15. Mesh Deformation of the Valve

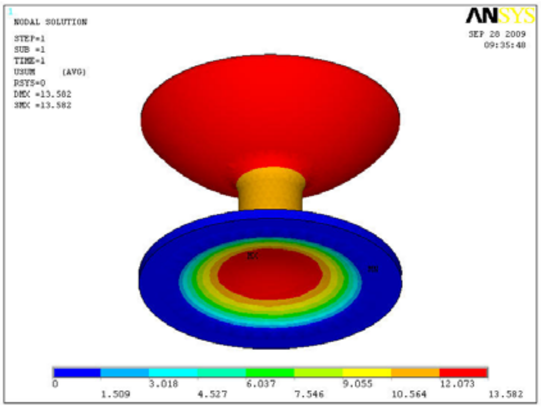


Figure 16. Total displacement of the valve

Stress Analyses. As shown in Fig.17, the stress of the upper disk is small, while the stress of the low disk is much higher, and the stress gradient of the low disk also changes much greater. As stress is one of the factors affecting the strain, pressure fluctuations affect the low disk of the valve more greatly. Long time running of the pump will cause many problems to the reflux valve, such as instability and fracture, so the low disk should be designed thicker.

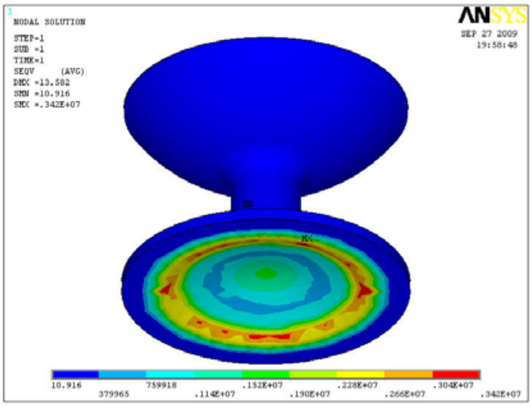


Figure 17. Stress Contour of the Valve

CONCLUSIONS

Combining with the unsteady numerical calculations and the experiments, the study indicates the influence pressure fluctuations on the reflux valve in the self-priming pump. Conclusions are as follows:

(1) From CFD unsteady simulation, we find that the pressure fluctuation amplitude at the first section with the reflux valve not closed is twice more than the pressure fluctuation amplitude with the valve closed completely. The fifth section has the minimum pressure difference between peak and average, which is 1.3%~2.4%.

(2) Using pressure sensors and LabVIEW, this paper obtained the pressures at the third, fifth and seventh sections in the volute. The experimental data indicate that the tendency of pressure fluctuations is consistent with unsteady numerical calculation. And the pressure difference in the fifth section is also minimal, 4%.

(3) Reflux hole should be placed at the fifth section, nearly 200° ~ 220° from the tongue along the direction of the impeller rotation in practice.

(4) The Finite Element Analysis (FEA) shows that the reflux valve can close the reflux hole completely after self-priming. But many problems, such as instability and fracture will be caused after a long time running of the pump. Therefore, the low disk of the valve should be designed thickened.

ACKNOWLEDGMENTS

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