Journal of Mechanical Science and Technology 24 (2) (2010) 575~582
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-009-1217-3

Experimental study on hydrodynamic performance of a cavitating centrifugal pump during transient operation[†]

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(Manuscript Received December 23, 2008; Revised July 18, 2009; Accepted November 16, 2009)

Abstract

An experimental study has been carried out in order to analyze the cavitation of a centrifugal pump and its effect on transient hydrodynamic performance during transient operation. The transient characteristics of the centrifugal pump were tested under various suction pressure and starting conditions. In transient operation of continuous starting and stopping process, instantaneous rotational speed, head, flow rate and suction pressure of the pump were measured. The effect of cavitation on transient performance of the centrifugal pump during transient operation was analyzed, and then the effects of starting acceleration rate and suction pressure of pump on cavitation were presented. Results showed that the cavitation would be delayed during rapid starting period. However, in the condition of low suction pressure and high rotational speed, pump cavitation is inescapable even if the starting period is less than a second. After the serious transient cavitation occurred, the transient performance of centrifugal pump would decline obviously, and the instantaneous head of pump would fluctuate.

Keywords: Centrifugal pump; Cavitation; Starting; Transient; Suction pressure; Experiment

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1. Introduction

As a fluid transportation and fluid power transmission equipment device, the centrifugal pump has been widely used in various fields. On ordinary occasions centrifugal pumps operate at steady-state, in other words, the rotational speed and hydrodynamic parameters of the pump are of a small change in running process. Such pump performance is expressed under steady and cavitation-free operating condition, and is called steady-state performance. However, as the field of centrifugal pump application has expanded and system complexity increased, more applications require controlling pump starting, stopping and other transient operation. As a result, the pump cavitation in those transient processes must be controlled effectively.

Numerous studies have been devoted to the steady-state performance of the centrifugal pump, and engineers can obtain satisfying results by using steady-state theory in pump design. However, for transient applications, the transient operation pumps still were designed by applying steady analysis and theory and ignoring transient effects. This approach was imprecise and could not achieve the best results, especially in the possible cavitation occasions. In recent years, more attention has been paid to the transient performance of pumps because of the growing engineering application needs. Tsukamoto et al. [1, 2] carried out an experimental and numerical study which investigated transient characteristics of a centrifugal pump during starting and stopping period. Results showed that the impulsive pressure and the lag in circulation formation around impeller vanes play dominant roles in the difference between dynamic and quasi-steady pump characteristics during the starting period. Thanapandi [3, 4] experimentally investigated a volute pump during transient starting and shut down with different discharge valve settings. A mathematical model was developed using the method of characteristics to analyze the transient characteristics of the pump. Results showed that the transient head characteristics closely follow the steady-state system head curve and the change of operating point is quasi-steady during normal starting and stopping transients. Lefebvre [5] conducted experiments on hydrodynamic performance of a centrifugal pump impeller during transient operation. The results obtained by Lefebvre showed that it put up substantial transient effects in overall impeller performance and the quasi-steady assumptions commonly used for the design of impellers that operate under high transient conditions are not valid. Wang and Wu [6-8] con-

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[†] This paper was recommended for publication in revised form by Associate Editor Won-Gu Joo

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ducted a series of experimental and numerical studies on transient performance of the centrifugal pump. It's indicated that the large-scale pump had more pronounced transient effect.

However, the above-mentioned investigation was in assurance to the case of cavitation-free flow. Cavitation characteristics are important performance indicators of the centrifugal pump, and for most pump systems cavitation was not allowed. The existing investigations about cavitation characteristics of the centrifugal pump essentially deal with the steady-state operation [9, 10]. Cavitation of the pump under transient operation was rarely investigated, but cavitation in the transient operating pump also has an important influence on the transient performance of the pump. Based on the investigation of the transient characteristics of non-cavitating centrifugal pumps, Tanaka and Tsukamoto [11-13] researched the transient behavior of a cavitating centrifugal pump at the sudden opening/closure of discharge valve and in rapid starting/stopping period. Cavitation behavior in the centrifugal pump was visualized by high speed video camera. Assuming that the transient pump performance is quasi-steady, an analytical study was made for the cavitating pump system. The results showed that the transient performance related to the time-dependent cavitation behavior, and pressure and flow-rate fluctuations occurred due to oscillating cavitation or water column separation at rapid transient operation.

To further study the transient hydrodynamic performance of cavitating centrifugal pump during transient operation, in this paper an experiment was carried out on cavitation characteristics of a transient operation pump. The effect of cavitation on transient performance was studied, and the distinction of the transient performance in a cavitation pump and non-cavitation pump was analyzed. The effects of starting acceleration and suction pressure condition on cavitation were analyzed.

2. Test equipment and test method

A special structure centrifugal pump was used for experiment and its principal specifications are summarized in Table 1. The meridian shape of the impeller is shown in Fig. 1; the pump configuration and test facility are illustrated schematically in Fig. 2. Various impellers and diffusers can be installed in the test section (water tank) to test their steady state performance or transient performance.

The inlet pipe from the pressure adjust tank to the water tank is 2500 mm in length and 300 mm in diameter. The diameter of the discharge pipe is 220 mm. The pressure adjust tank is 1.5 m^3 in volume and its pressure adjusted by vacuum pump.

The test pump is driven by an air turbine, which controls the rotational speed and starting acceleration rate of the test pump. This drive system can perform significant adjustment on rotational speed and various transient operations.

The instrumentation system in the test facility has good transient response capability. Time intervals of data acquisition for all channels are 0.0005 s. The measure of grounding and signal isolation was adopted to reduce the signal noise of instrumentation and data acquisition system. The instantaneous flow rate was measured by an electromagnetic flowmeter installed in the suction pipe line. The suction pressure, discharge pressure and tank pressure were measured by semiconductor type pressure transducers, which were installed in the pipe line and tank directly. The instantaneous torque and rotational speed were measured by a torque/rotational speed sensor installed between the air turbine and pump shaft.

A desired value was set for the manual adjusting valve in the discharge pipe line before transient operation, which was kept constant during the transient operation period. For transient cavitation testing, the original pressure of the pipe loop system was adjusted to a lower level by a vacuum pump before transient operation, and then the transient hydrodynamic performance was tested in various cavitating degrees.

Table 1. Specifications of the test pump.

Parameter	Value
Suction diameter D_1 (mm)	300
Discharge diameter D_2 (mm)	220
Rotational speed n (r/min)	1200
Head H (m)	24
Flow rate Q (m^3/s)	0.3
Net positive suction head NPSHr (m)	4.5
Number of vane Z	5

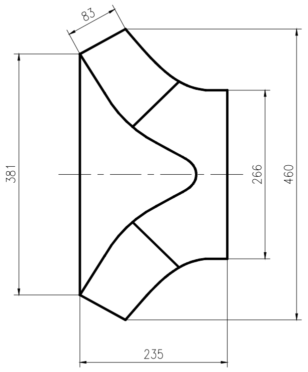

Fig. 1. The meridian shape of the impeller.

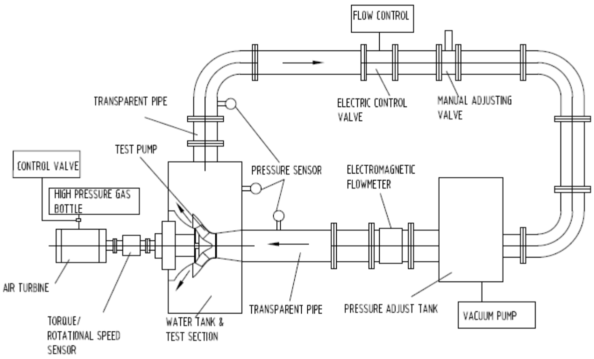

Fig. 2. Schematic view of test system.

3. Transient performance of non-cavitation pump

The steady state performance and transient performance of a non-cavitating centrifugal pump were tested before the cavitation experiment during transient operation. The cavitation-free results formed the basis for primary transient characteristics analysis to which the cavitation results were compared. Fig. 3 presents the steady state performance of the pump, and Figs. 4, 5 and 6 present the transient hydrodynamic performance of the pump with low acceleration, mid acceleration and high acceleration respectively. Time histories of rotational speed n, flow rate Q, head H and the quasi-steady assumption head H_s of pump are shown in the figures. In the quasi-steady assumption, the pump performance under all instantaneous rotational speed during transient operation was derived from the steady state performance shown in Fig. 3 by similarity law. The pump similarity law is expressed as:

$$\frac{Q_s}{Q_m}=\frac{n_i}{n_m},\ \frac{H_s}{H_m}=\left(\frac{n_i}{n_m}\right)^2 \qquad (1)$$

where Q_s, H_s and n_i are the quasi-steady assumption flow rate and head under instantaneous rotational speed n_i during transient operation period, Q_m and H_m are the steady state flow rate and head under rated rotational speed n_m (here is 1200 r/min). Some parameters are shown in Table 2, which describes the difference between transient performance and quasi-steady assumption performance. In Table 2, the acceleration rate of rotational speed is defined as the average acceleration before the rotational speed arriving at 90% of $n_{\max}$.

In the case of unsteady flow rate, the test value of pressure obtained from the upstream and downstream pressure sensors is affected by hydraulic transients in the looped pipeline. The total pressure difference is generated mainly by the pump, and is also affected by the inertia of the water contained in the pump and pipeline. The additional pressure rise is not seen by the pressure sensors because it is used to accelerate the fluid mass within the impeller and water tank. Ideally, this mass term should be added to the measured head H. However, the mass term affected head H by no more than 1.5 percent, and this term had less of an effect on head H than the inaccuracy incurred from differentiating the flow-rate data. Similar to reference [5], the additional pressure rise to accelerate the fluid mass was omitted.

As shown in Figs. 4-6 and Table 2, the *tn*-curve includes rapid rise phase, slow decline phase and rapid decline phase. The flow rate Q and head H of pump change rapidly with rotational speed n changes during transient operation. The time of head H arriving at its peak value is close to that of rotational speed n, the flow rate Q still increases after head H and rotational speed n arrive at their peak value because of the steady state operating condition of pump not being reached. The instantaneous head H is higher than the quasi-steady assumption head H_s obviously during rapid rise phase of *tn*-curve, and the difference between instantaneous head and quasi-steady assumption head is markedly affected by acceleration rate. During the rapid decline phase of the *tn*-curve, the head H begins lower than the quasi-steady assumption head H_s. In the low acceleration, mid acceleration and high acceleration starting process, the acceleration rates are 148 rad/s^2, 175 rad/s^2 and 225 rad/s^2, and the peak values of the head are 19.0 m, 24.5 m and 37.0 m, respectively. Corresponding to the same instantaneous flow rate Q and rotational speed n, the quasi-steady assumption head H_s of three transient processes are 15.0 m, 18.4 m and 25.0 m, respectively. Hence, the peak values of instantaneous head are 1.27, 1.33 and 1.48 times the values of quasi-steady assumption head, respectively, in the low acceleration, mid acceleration and high acceleration operations. It is shown that the rapid starting pump appears high peak value of head, and that the higher the acceleration is, the greater the difference between instantaneous head and quasi-steady assumption head. This tendency is mainly caused by the effect of the additional impulsive pressure related to the impeller angular acceleration. During transient operation period, the theoretical instantaneous head H could resolve into a steady term, an angular acceleration term and an inertial term [8]. During the rapid rise phase, the angular acceleration term increases the instantaneous head H markedly, and inertial term had slight effect. In addition to this effect, the instantaneous head H also was affected by the velocity profile variations in the impeller. During the rapid rise phase of *tn*-curve, the flow separation was delayed and the whole flow in the impeller behaved like the potential flow. It also leads to a greater value for instantaneous head H than the quasi-steady assumption value H_s.

Similar to the results obtained by Tsukamoto [1] and Lefebvre [5], acceleration has a profound effect on the transient characteristics of a centrifugal pump. The transient performance has an obvious difference from the quasi-steady assumption results, and the peak value of head is markedly affected by the acceleration rate.

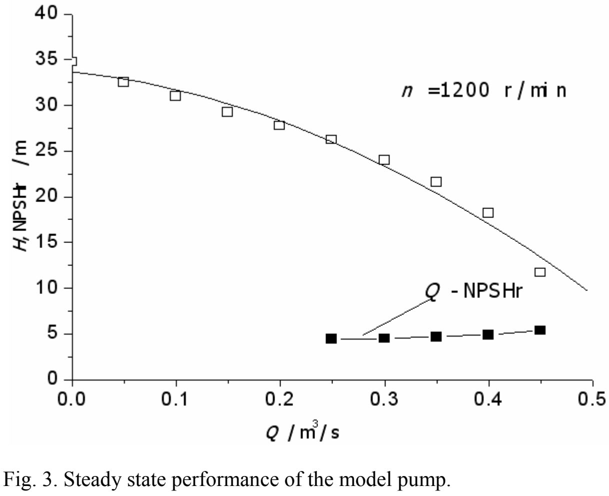

Fig. 3. Steady state performance of the model pump.

Table 2. Transient parameters of non-cavitating pump.

	Fig. 4 (Low acceleration)	Fig. 5 (Mid acceleration)	Fig. 6 (High acceleration)
t_a (s)	0.58	0.55	0.51
n_{max} (r/min)	910	1020	1220
a (rad/s^2)	148	175	225
Q_{max} (m^3/s)	0.22	0.26	0.33
H_{max} (m)	19.0	24.5	37.0
H_s (m)	15.0	18.4	25.0
H_{max}/H_s	1.27	1.33	1.48

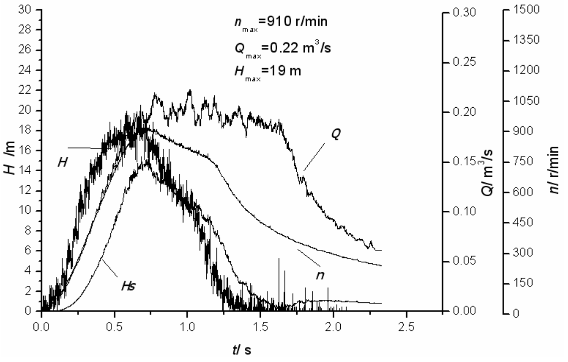

Fig. 4. Hydrodynamic performance of non-cavitating pump during low acceleration (low rotational speed) transient operation.

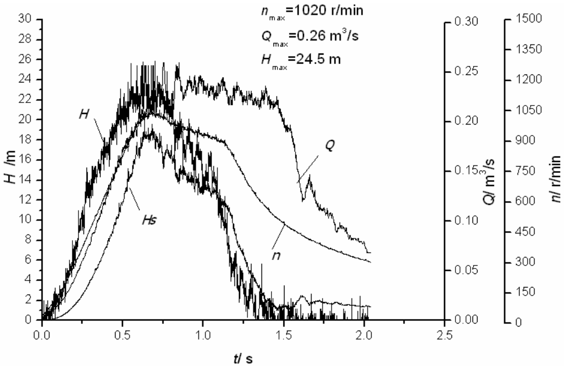

Fig. 5. Hydrodynamic performance of non-cavitating pump during mid acceleration (mid rotational speed) transient operation.

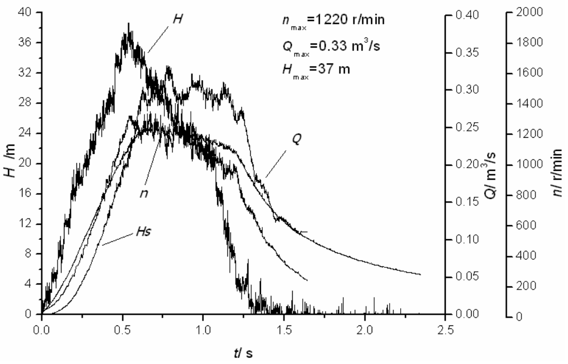

Fig. 6. Hydrodynamic performance of non-cavitating pump during high acceleration (high rotational speed) transient operation.

4. Transient characteristics of cavitating pump

During cavitation-free transient operation, the suction pressure of the test pump is about 1.5 mH_2O (gauge pressure, following the same). To test the general characteristics of the cavitating pump during transient operation, the suction pressure of pump was adjusted to a low value by vacuum pump, and the maximum rotation speed n_{max} was adjusted to more than 1200 r/min. Fig. 7 presents the transient performance of the cavitating pump with low suction pressure (-8.6 mH_2O) and high rotational speed (1520 r/min).

As shown in Fig. 7, affected by the serious cavitation during the starting period, the transient hydrodynamic performance of pump obviously decreased compared with that of the cavitation-free operation. During the rapidly rising phase of rotational speed, the increasing instantaneous head H suddenly declines and shows fluctuant state after the rotational speed exceeds a critical speed (here is 985r/min). Before arriving at the critical speed, the instantaneous head H is higher than the quasi-steady assumption head H_s obviously. However, the instantaneous head H begins lower than the quasi-steady assumption head H_s after arriving at the critical speed. From the results of cavitation-free operation shown in Fig. 4, Fig. 5 and Fig. 6, the transient head is obviously higher than the quasi-steady assumption head during whole rapid rise phase of rotational speed. It indicated that the decline of instantaneous head was caused by cavitating of the pump. The starting process keeps less than a second during transient operation, but cavitation cannot be avoided as the rotational speed and flow rate increase.

As mentioned above, the instantaneous head H of the non-cavitation pump tends to become larger than the quasi-steady assumption head H_s during rising phase of rotational speed, and head H increases rapidly with increasing n. However, as shown in Fig. 7, the increasing head H suddenly declines at stage (c) when n is still increasing. A similar phenomenon was observed in reference [12]; the phenomenon of head sudden decline is the result of cavitation in the transient operation period. In the Tanaka study, the behavior of the cavitation

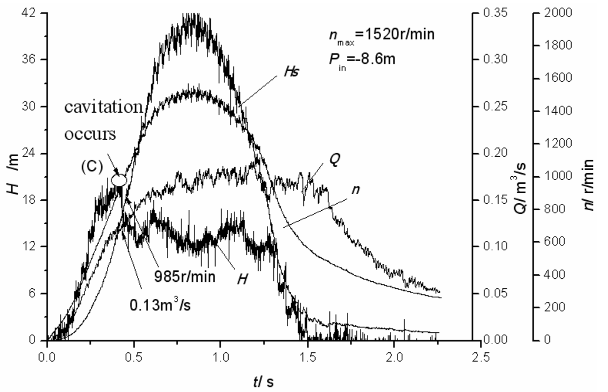

Fig. 7. Hydrodynamic performance during the transient operation under cavitation condition.

inside the impeller is visualized through the transparent wall casing and suction pipe by high speed video camera. Cavitation bubbles were observed near the leading edge of the impeller vanes at stage (c) and continued to grow in volume with increasing *n*, but the cavitation bubbles was not observed before passing through stage (c). The inflection point of the *tH*-cuve at rapid rise phase corresponds to the obvious cavitation inception. Hence, we defined the inflection point of *tH*-cuve as the critical position of cavitation inception.

However, it is still difficult to accurately find the cavitation inception position during transient operation in an actual process. In this paper, the critical rotational speed n_c and corresponding flow rate Q_c were used to approximately estimate the cavitation inception. To distinguish between head decline caused by cavitation and other light pressure fluctuations, we chose the conditions of obvious cavitation occurring to analyze the transient cavitation, and regarded occurrence of head H lower than the quasi-steady assumption head H_s as one of the cavitation indicators. Hence, the critical position of cavitation inception was defined as the last inflection point of *tH*-cuve before the instantaneous head H begin lower than the quasi-steady assumption head H_s. In other words, the critical position was determined by the comparison of the *tH*-curve and tH_s-curve. According to the above definition, the critical rotational speed n_c is 985r/min, critical flow rate Q_c is 0.13m^3/s in Fig. 7.

From the *tQ*-curve, the flow rate Q presents more moderate increases and the maximum flow rate Q_{max} of cavitating pump obviously decline during the transient operation. This is because the flow rate of the pipe loop system and pump is increased by pump pressure head, and the pressure markedly declines due to cavitation in the pump.

To analyze the relations of rotational speed n, flow rate Q, suction pressure P_{in} and cavitation, the non-dimensional cavitation coefficient k is defined as follows:

$$k = \frac{2\pi n\sqrt{Q}}{60(gH_o)^{3/4}} \tag{2}$$

where n is the pump rotational speed, Q is the pump flow rate, g is the acceleration of gravity, and H_0 is the net positive suction head (NPSH) of system. The critical cavitation coefficient k_c is defined as that pump cavitation occurs when $k \geq k_c$. It indicates that the greater the k_c is, the better cavitation performance the pump has. Hereon, the coefficient k is used to analyze the effect of cavitation delayed in the transient operation process.

In the transient operation shown in Fig. 7, the critical rotational speed is 985 r/min, flow rate is 0.13m^3/s, and the NPSH of system is 1.4 m, the critical cavitation coefficient k_c is 5.21 by formula (2). However, during the steady state operation, the critical rotational speed of cavitation inception is about 710r/min with the same suction pressure and flow rate conditions, and the critical cavitation coefficient k_c is 3.76 (it is operated at low flow rate point, but the steady state cavitation coefficient k_c is 4.02 at the best effective point). It indicated that the pump cavitation was obviously delayed during the rapid starting period. The phenomenon of cavitation delayed may be associated with the impulse pressure of pump startup which was explained by Tsukamoto [1]. During the rapid rise phase of rotational speed, flow in pump behaves like potential flow without separation. Therefore, it leads to a greater value for head H than quasi-state assumption head H_s, and also leads to the delay of cavitation inception.

Table 3. Transient parameters of cavitating pump.

	Fig. 7	Fig. 8	Fig. 9	Fig. 10	Fig. 11
t_a (s)	0.58	0.62	0.66	0.65	0.65
n_{max} (r/min)	1520	1170	930	1020	1020
a (rad/s^2)	247	178	133	148	148
P_{in}(m)	-8.6	-8.9	-8.5	-8.3	-9.0
n_c (r/min)	985	770	780	875	675
Q_c (m^3/s)	0.13	0.12	0.14	0.16	0.12
k_c	5.21	4.67	4.06	4.43	4.42

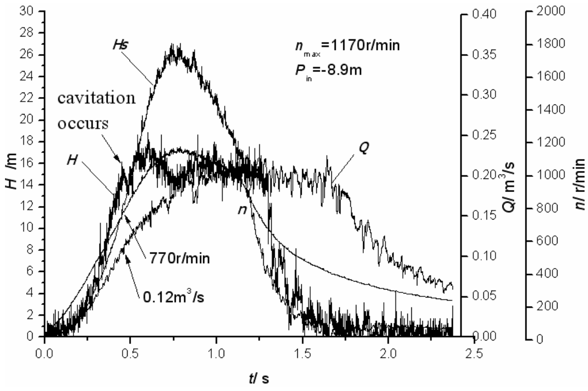

Fig. 8. Hydrodynamic performance of the cavitating pump during high acceleration transient operation.

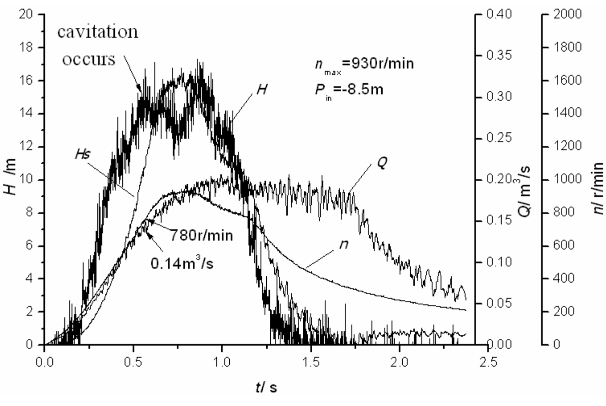

Fig. 9. Hydrodynamic performance of the cavitating pump during low acceleration transient operation.

5. Effect of starting conditions on pump cavitation

5.1 Effect of acceleration rate and rotational speed

To further analyze the influence of starting conditions on pump cavitation during transient operation, we tested the transient performance of the cavitating pump with different acceleration rate. As shown in Fig. 8, Fig. 9 and Fig. 10, similar to the results of Fig. 7, in transient operation process, the phenomenon of transient performance declines and the instantaneous head H begins lower than the quasi-steady assumption head H_s after cavitation occurs. Some typical instantaneous parameters of cavitating pump are shown in Table 3, which describes the operation condition and the critical parameters of transient cavitation.

As shown in Table 3, the acceleration rates of rotational speed are 247 rad/s^2, 178 rad/s^2, 133 rad/s^2 and 148 rad/s^2 in Fig. 7, Fig. 8, Fig. 9 and Fig. 10, and the critical cavitation coefficient k_c is 5.21, 4.67, 4.06 and 4.43 respectively. Along with the acceleration rate a increase, the critical cavitation coefficient k_c clearly increases. It indicates that the acceleration rate has a significant effect on the cavitation and the transient performance during transient operation period, and the pump cavitation would be further delayed when the starting acceleration rate increased in transient operation period. This tendency is mainly caused by the flow in starting the pump where the shear layer and vortical structures are more intense and compact for higher accelerations; the delayed flow separation may be also delaying the cavitation inception.

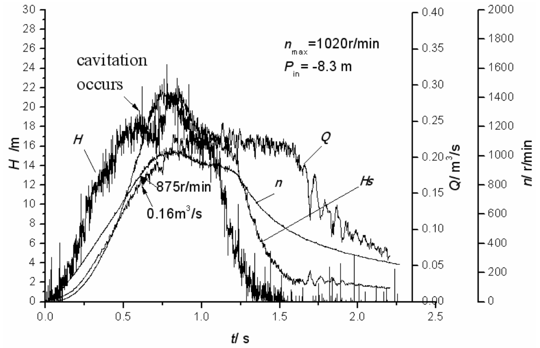

Fig. 10. Hydrodynamic performance of the cavitating pump during transient operation with high suction pressure.

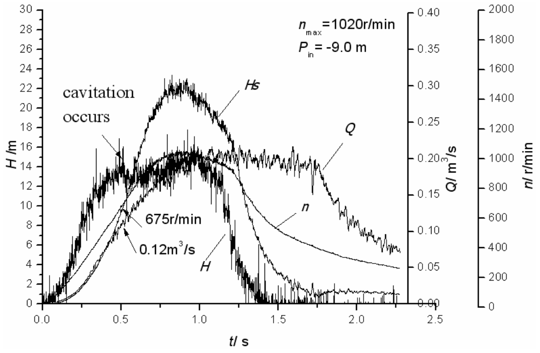

Fig. 11. Hydrodynamic performance of the cavitating pump during transient operation with low suction pressure.

5.2 Effect of suction conditions

To further analyze the influence of suction pressure on pump cavitation during transient operation, Fig. 10 and Fig. 11 present the transient performance of the cavitating pump with high and low suction pressure, respectively. Two tran sient processes have the same maximum rotational speed and acceleration rate, but the suction pressure is -8.3 mH$_2$O and -9.0 mH$_2$O, respectively.

As shown in Fig. 10 and Fig. 11, the maximum rotational speed and the accelerating rate of the transient process are 1020 r/min and 148 rad/s^2, which is similar to those shown in Fig. 5. Pump cavitation occurs and the transient performance declines when the suction pressure decreases during transient operation. In the cavitation-free transient operation shown in Fig. 5, the peak value of head is 24.5 m. As the suction pressure drops, the peak value of head drops to 21m and 16 m in the transient process shown in Fig. 10 and Fig. 11. In the high suction pressure transient process, the critical rotational speed of cavitation inception is 875r/min, the critical flow rate is 0.16m^3/s, and the critical cavitation coefficient k$_c$ is 4.43. And corresponding parameters in low suction pressure transient process are 675 r/min, 0.12 m^3/s and 4.42 respectively.

In addition, instantaneous head fluctuates and arrives at a new peak value during the transient operation shown in Fig. 10. This maybe due to the not fully developed cavitation, and the cavitation was alleviated after the rotational speed decreased.

6. Conclusions

An experimental study was performed on the transient performance of a centrifugal pump at various suction pressures and accelerations during the transient operation period. Results showed that the dynamic performance of the centrifugal pump was related to the cavitation of the pump during the low suction pressure starting period.

In the starting period of the non-cavitation pump, acceleration has a profound effect on transient characteristics of the centrifugal pump. The instantaneous head tends to become larger than the quasi-steady assumption head, and the peak head in rapid rise phase is markedly affected by the acceleration rate. The additional impulsive pressure related to the impeller angular acceleration is the primary reason for this characteristic.

Under the low suction pressure and high rotational speed conditions, the pump cavitation will occur during a second starting period and the transient performance will decline obviously. During the cavitation-free transient operation period, the maximum head of the non-cavitating pump is obviously higher than the quasi-steady assumption value, and the peak value of head increases as the starting acceleration increases. However, after the cavitation of transient operation occurred, the peak head firstly obviously declined then began to fluctuate.

The pump cavitation will be delayed during the rapid starting period. Under the same rotational speed and suction pressure conditions, the higher the starting acceleration, the greater the critical rotational speed and critical cavitation coefficient. Cavitation will occur and come to be severe with the decline of suction pressure. However, the transient performance will still improve and fluctuate as the rotational speed increases under relatively light cavitation. Those phenomena indicated that the serious cavitation and performance drop could be avoided under relatively dissatisfactory suction conditions during transient operation.

The cavitation inception and development of centrifugal pump are complicated during transient operation. Future investigations on the cause of pump cavitation will be done according to the details of internal flow. In addition, the numerical prediction of cavitation inception and performance drop during transient operation also will be further studied.

Acknowledgment

This study was performed as part of National Natural Science Foundation of China, the project number is 50906074. The support is gratefully acknowledged.

Nomenclature

Q, Q_i : Flow rate [m^3/s]
Q_s : Quasi-state assumption flow rate [m^3/s]
Q_m : Steady state flow rate [m^3/s]
Q_c : Critical flow rate of cavitation [m^3/s]
H, H_i : Total head [m]
H_s : Quasi-state assumption head [m]
H_m : Steady state head [m]
P_in : Suction pressure head [m]
n, n_i : Rotational speed [r/min]
n_max : Maximum rotational speed [r/min]
n_c : Critical rotational speed of cavitation [r/min]
n_m : Rated rotational speed [r/min]
k : Cavitation coefficient
k_c : Critical cavitation coefficient
a : Angular acceleration rate [rad/s^2]
g : Acceleration of gravity [m/s^2]
$NPSH_\mathrm{r}$: Required net positive suction head [m]
H_0 : Net positive suction head of system [m]
D_i : Suction diameter of impeller [mm]
D_2 : Discharge diameter of impeller [mm]
Z : Number of impeller vane
t_a : Accelerating time [s]

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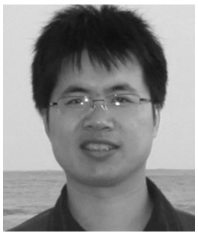

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