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Performance Characteristics and Cavitation Conditions of Three Axial-Flow Pump Impellers*

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In order to obtain wider and better performances of an axial-flow pump, the suction performances must be improved.

Three impellers having different solidities and blade sections were tested to study the overall- and suction-performances and to observe the cavitation conditions inside the impellers.

The additional head loss due to cavitation and the head rise ratio have been shown as the function of the product of cavitation parameter by solidity. The cavitation zone parameter has been illustrated as the pressure distribution on the blade surface. The suction performance may be estimated from it.

1. Introduction

The performance of an axial-flow pump has been studied for years by G. F. Wislicenus⁽¹⁾, M. J. Miller et al.⁽²⁾, T. Toyokura⁽³⁾, W. Scheer⁽⁴⁾, T. Kasai et al.⁽⁵⁾ and T. Toyokura et al.⁽⁶⁾. The flow inside an axial-flow impeller has been investigated by T. Ikui⁽⁷⁾ and T. Watanabe⁽⁸⁾. The cavitation limit was reduced from the lift coefficient by C. Pfeleiderer⁽⁹⁾ and T. Ikui⁽¹⁰⁾. The experimental investigations of cavitation were carried out by T. Horie and K. Kawaguchi⁽¹¹⁾, M. Oshima⁽¹²⁾ and M. J. Hartmann⁽¹³⁾. The breakdown condition due to cavitation was investigated by G. F. Wislicenus⁽¹⁴⁾. Recently, for the purpose of developing a pump with high head and high speed, the suction performance of a helical inducer has been investigated by L. B. Stripling and A. J. Acosta⁽¹⁵⁾. Their investigations are very worthy of note.

The pressure distributions on the blade element of impellers closely relate to the suction performance, but the studies on the relationship between them are scarce. It should be affected by the setting condition and the profile of the blade element in a cascade. Therefore the observation of the cavitation zone is very important.

In this report, three impellers having different

solidities and blade sections are tested to study the overall- and suction-performance and to observe the cavitation inside the impellers. The main results of the investigation are as follows.

The additional head loss due to cavitation and the head rise ratio are shown as a function of the product of cavitation parameter by solidity. The impeller with "laminar profile" is extremely superior in the suction performance to the other impellers. The cavitation zone is illustrated as the pressure distribution on the blade.

2. Nomenclatures

The following nomenclatures are used in this paper.

- A : cross-sectional area of flow path
- g : acceleration of gravity
- H : total head
- $H_i \{= L_e / (\gamma Q)\}$: input head
- h_{ic} : additional head loss due to cavitation
- $\Delta h \{= (P_1 - P_v) / \gamma\}$: difference between static pressure head at impeller inlet and saturated vapor pressure head
- K : symbol of cavitation zone
- $k_s \{= \Delta h / (w_1^2 / 2g)\}$: cavitation number
- L_e : effective shaft power
- l : chord length of blade element
- l/t : solidity
- $\text{NPSH} \{= (P_{t1} - P_v) / \gamma\}$: net positive suction head
- n : speed of rotation
- P_t : total pressure
- P : static pressure
- P_v : saturated vapor pressure

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Q : flow-rate
 r : radius
 t : blade spacing
 u : circumferential velocity of impeller
 v_m : meridional velocity of fluid
 v_u : absolute tangential velocity of fluid
 w : relative velocity of fluid
 γ : specific weight of water
 η_e : internal efficiency
 $\nu (=r_e/r_a)$: boss ratio
 $\pi_e \{=L_e/(\gamma Au^3/2g)\}$: power coefficient
 $\tau \{=NPSH/(u^2/2g)\}$: cavitation parameter
 $\phi (=v_m/u)$: flow coefficient
 $\psi \{=H/(u^2/2g)\}$: head rise coefficient
 $\psi_i \{=H_i/(u^2/2g)\}$: input head coefficient
 Subscripts
 a : blade tip
 c : cavitation condition
 cz : cavitation zone
 e : blade root
 nc : non-cavitation condition
 opt : optimum condition of non-cavitation
 1 : impeller inlet
 2 : impeller outlet

Other symbols and subscripts are defined when they appear in the text.

3. Test facilities and test procedures

A schematic diagram of the facilities is shown in Fig. 1. The pump speed was observed by the electronic counter and the shaft power was measured with the D. C. dynamometer. The volume flow-rate was measured by the multi-hole tubes with an aerofoil section at the inlet side of the pump, which were calibrated with multi-total-pressure tubes. The pump total head was obtained from the difference of the static pressure between the outlet and the inlet

of the pump.

The test impellers are named G 1 type, CY 1 type and NA 1 type, respectively. The impeller CY 1 and NA 1 were designed by the procedure involving the cascade theory⁽¹⁶⁾. The impeller CY 1 has blade profiles of Clark Y and the impeller NA 1 has blade profiles of NACA-16 series.

The main specifications of the test pumps are summarized in Tables 1 and 2. The main design dimensions of the impellers are summarized in Table 3. Figure 2 shows a sectional view of the pump. Figure 3 is a photograph of the test impellers.

Each impeller was operated at 900, 1200, 1500 and 1800 rpm. The suction performance tests were conducted by reducing the suction head at a constant pump speed and a constant flow-rate. The inception and the growth of cavitation inside the impellers were observed by a stroboscope and photographed by means of microflashes. As the

Fig. 1 Schematic diagram of test facilities

Table 1 Design specifications of test pump

Specifications	Flow-rate	Total head	Speed of rotation	Flow coefficient	Head rise coefficient	Specific speed	Dimensionless specific speed
Symbols	Q m ³ /sec	H mAq	n rpm	ϕ_a	ψ_a	n_s (m, m ³ /sec, rpm)	σ
Impeller type							
G 1	0.20	6.00	2000	0.204	0.149	233.0	1.475
CY 1 NA 1	0.20	6.23	1500	0.268	0.272	169.5	1.073

Notice: The impellers G 1, CY 1 and NA 1 denote the profile of approximate Göttingen, Clark Y and NACA-16 series, respectively.

Table 2 Main dimensions of test pump

Dimensions	Casing diameter	Rotor outer diameter	Boss diameter	Blade span	Tip clearance	Boss ratio	Tip clearance span ratio	Number of impeller vanes	Number of guide vanes
Symbols	D mm	D_a mm	D_e mm	s mm	c mm	ν	c/s %	z	z_g
Impeller type									
G 1	271.0	269.0	170.0	49.5	1.25	0.63	2.53	3	6
CY 1 NA 1	271.5	270.0	170.0	50.0	0.75	0.63	1.50	4	6

casing of the pump is made of lucite and each surface of the casing is graduated with perpendicular pitch lines, the size and the location of cavitation zone inside the impeller can be quantitatively observed.

4. Cavitation zones and cavitation coefficients

The inception and the growth of cavitation were

Fig. 2 Cross-sectional view of test axial-flow pump

(a) Impeller CY1 (2) Impeller NA1
Fig. 3 Photographs of test impellers

observed by the flow visualization methods. The cavitation zones were classified as shown in Fig. 4. Figure 5 shows the typical cavitation in the impeller NA1.

The cavitation parameter τ or the cavitation number k_s is defined as follows.

$$\tau = \left(\frac{P_{t1} - P_v}{\gamma} \right) / \left(\frac{u^2}{2g} \right) = \text{NPSH} / \left(\frac{u^2}{2g} \right) \\ = \left\{ \Delta h + \frac{(\phi u)^2}{2g} \right\} / \left(\frac{u^2}{2g} \right) \quad \dots\dots (1)$$

Fig. 4 Classification of cavitation zone

Table 3 Main design parameters of test impellers

Impeller type		G1					CY1					NA1				
Blade section	Name	a'	b	c	d	e'	a	b	c	d	e	a	b	c	d	e
	Diameter D mm	267.0	244.0	219.0	194.0	179.0	270.0	245.0	220.0	195.0	170.0	270.0	245.0	220.0	195.0	170.0
	Circumferential velocity of impeller u m/sec	28.00	25.59	22.97	20.34	18.77	21.21	19.24	17.28	15.32	13.35	21.21	19.24	17.28	15.32	13.35
	Meridional velocity of fluid v_m m/sec	5.834	5.834	5.834	5.834	5.834	5.799	5.799	5.799	5.799	5.799	5.799	5.799	5.799	5.799	5.799
	Absolute tangential velocity of fluid v_u m/sec	4.621	5.056	5.633	6.361	6.893	3.458	3.811	4.244	4.788	5.492	3.458	3.811	4.244	4.788	5.492
	Chord length l mm	170.0	158.0	143.0	130.0	123.0	212.1	192.4	172.3	153.2	133.5	212.1	192.4	172.3	153.2	133.5
	Blade spacing t mm	280.0	256.0	229.0	203.0	188.0	212.1	192.4	172.3	153.2	133.5	212.1	192.4	172.3	153.2	133.5
	Solidity l/t	0.607	0.617	0.625	0.640	0.654	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Blade setting angle θ	15°40'	17°05'	19°05'	21°37'	23°25'	18°43'	20°59'	23°48'	28°05'	34°29'	16°51'	19°40'	23°10'	27°56'	34°00'
Blade section		Approximate Göttingen*					Clark Y**					NACA 16***				
		491	492	488	474	596	4%	6%	8%	10%	11.7%	504	506	508	710	10(11.7)

- Notice: 1. In the above table, the blade sections a' and e' of G1 do not stand for blade tip and blade root, respectively.
 2. In the above table, the absolute tangential velocity of fluid for G1 uses the value at the best efficiency point of the overall performance, because the design parameters are deficient.
 3. References of blade sections.
 * L. Prandtl and A. Betz. Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen III, N, (1935, 1932), Verlag von R. Oldenbourg.
 ** Y. Asano et al.: Handbook of Hydraulic Machinery, (1962), p. 91, Corona Co.
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$$k_s = \left(\frac{P_1 - P_v}{\gamma} \right) / \left(\frac{w_1^2}{2g} \right) = \Delta h / \left(\frac{w_1^2}{2g} \right) \left. \vphantom{\frac{P_1 - P_v}{\gamma}} \right\} \dots \dots \dots (2)$$

$$= \Delta h / \left\{ \frac{u^2}{2g} (1 + \phi^2) \right\}$$

The relation between τ and k_s is given by

$$\tau = k_s(1 + \phi^2) + \phi^2 \dots \dots \dots (3)$$

Relating with the performance of a blade element, the circumferential velocities in Eqs. (1), (2) and (3) correspond to respective radii of the impeller.

Table 4 shows the main characteristic values of the test impellers. The characteristic curves of three impellers are shown in Fig. 6.

The influences of cavitation on the head coefficient are illustrated in Fig. 7. The inception lines of cavitation are shown by chain lines. In Figs. 7 and 8, K without subscript a or e , implies that the cavitation spreads over the blade span. As K_3 could not always be clearly distinguished from K_1 , it was also regarded as the inception of K_3 when K_1 extended from the blade leading edge to about 20 percent in location of the chord length. K_1 , K_2 and K_3 shown in the cavitation test of wing sections

Table 4 Main characteristics of test impellers

Impeller type		G1	CY1	NA1
Characteristics				
Values at the optimum-operating efficiency	Flow coefficient ϕ_{aopt}	0.215	0.245	0.230
	Head rise coefficient ψ_{aopt}	0.229	0.349	0.339
	Power coefficient π_{eaopt}	0.732	1.058	0.990
	Internal efficiency η_{eopt}	0.673	0.808	0.788
	Input head coefficient ψ_{iaopt}	0.341	0.432	0.430
	Dimensionless specific speed σ_{opt}	1.088	0.847	0.838
	Specific speed n_{sopt} (m, m ³ /sec, rpm)	171.6	133.5	132.2
Values at the shut off	Head rise coefficient ψ_{as}	0.463	0.764	0.768
	Power coefficient π_{eas}	1.110	2.160	2.050
	Head rise ratio ψ_{as}/ψ_{aopt}	2.022	2.189	2.266
	Power ratio π_{eas}/π_{eaopt}	1.516	2.042	2.072

and K_4 shown at the tip clearance, have been well known. K_5 and K_6 were observed in the test of the impellers CY1 and NA1. It may be thought that K_5 arises from the mutual interference of boundary layer on the hub surface and the impeller blade, and that K_6 results from the local separation on the rear upper-surface of the blade section b or c as the impeller works at high head.

Figure 7 shows also that the head coefficients fall a little as the cavitation K_4 occurs, and that they rise and fall somewhat as K_2 and K_3 grow, and that they break down abruptly as the both cavitations grow to a considerable extent. The impeller NA1 has shown smaller cavitation numbers for inceptions and breakdown points than the others for a wide range of flow-rates. Figure 9 shows the cavitation performances of the test impellers.

Fig. 6 Overall performances for test pump

(a) $\phi_a = 0.212$ $\phi_a = 0.380$
 $k_{sa} = 0.219$ $n = 1500$ rpm
 (b) $\phi_a = 0$ $\phi_a = 0.760$
 $k_{sa} = 0.728$ $n = 900$ rpm
 Fig. 5 Typical photographs of the cavitation, impeller NA1

Fig. 7 Head rise coefficient ψ_a versus cavitation number k_{sa} for various flow coefficients Fig. 8 Cavitation number k_{sa} versus flow coefficient ϕ_a for various cavitation inceptions

Fig. 9 Dimensionless characteristic performances of test impellers for various cavitation numbers k_{sa} Fig. 10 Cavitation performance: Head rise ratio ψ_a/ψ_{anc} versus variable $\tau_a(l/t)_a$

5. Effects of solidities and blade profiles on the suction performance

Figure 10 shows the relations between the head rise ratio ψ_a/ψ_{anc} and the variable $\tau_a(l/t)_a$. The variables imply the effect of pressure loading for a

Fig. 11 Cavitation performance: Additional head loss due to cavitation $h_c/(u_a^2/2g)$ versus variable $\tau_a(l/t)_a$

given head rise. It is seen from Fig. 10 that the cavitation performance curves of the impellers G1, CY1 and NA1 considerably converge to each other, and that some discrepancy between CY1 type and NA1 type arises from the influence of the location of the maximum blade thickness. It is thought that the impeller NA1 has a smaller pressure drop on the upper blade surface than the others for a given head rise. This is also explained from the results of the observation of cavitation zone in Chapter 6.

The pressure distribution on the blade surface, the input head and the head loss in a pump are

affected by cavitation. The head losses with or without cavitation may become Eqs. (4) and (5), respectively. Therefore the additional head loss due to cavitation may be described by Eq. (6) and its non-dimensional form becomes Eq. (7).

$$\Delta H_{inc} = H_{inc} - H_{nc} = \{L_{enc}/(\gamma Q)\} - H_{nc} \dots \dots (4)$$

$$\Delta H_{lc} = H_{lc} - H_c = \{L_{ec}/(\gamma Q)\} - H_c \dots \dots (5)$$

$$h_{lc} = \Delta H_{lc} - \Delta H_{inc} = (H_{lc} - H_c) - (H_{inc} - H_{nc}) \dots \dots (6)$$

$$\left. \begin{aligned} h_{lc} / \left(\frac{u_a^2}{2g} \right) \\ = \{ (H_{lc} - H_c) - (H_{inc} - H_{nc}) \} / \left(\frac{u_a^2}{2g} \right) \\ = (\psi_{anc} - \psi_{ac}) - (\psi_{inc} - \psi_{ic}) \end{aligned} \right\} \dots (7)$$

Figure 11 shows the additional head loss due to cavitation. It is recognized that the additional head

loss increases as the flow-coefficient decreases, and that the loss has a maximum value near by $\tau_a(l/t)_a \approx 0.15$.

6. Cavitation zones on blade surface

The cavitation inception on an aerofoil in two dimensional flow occurs at a position where the minimum pressure occurs. As the total pressure of the main flow decreases much more, cavitation spreads over a part of the surface, i.e. the part may be described as a cavitation zone.

The cavitation zone of the test impeller was observed by the synchronized strobo light under various suction conditions, i.e. various cavitation parameters.

In this report, cavitation zone parameter is used only when cavitation occurs, and it is distinguished from cavitation parameter which is also used in case of no cavitation.

In Figs. 12, 13 and 14, the chordwise positions of the front and rear ends of the cavitation zone on each of the blade sections a, b, ... e are successively plotted for various cavitation zone parameters.

For example, it is illustrated by Fig. 14 (b) that under the operating condition $\phi_a = 0.24$, $\psi_a = 0.305$ and $\tau_{cz} = 0.4$, the cavitation zone extends over almost the full chord length of the blade section e, extends from $x/l = 0.05$ to $x/l = 0.6$ on the section d, extends from $x/l = 0.15$ to $x/l = 0.25$ on the section c, and does not exist on the sections b and a.

Fig. 12 Test results of cavitation zone parameter τ_{cz} on various blade sections of impeller G1
Notice: In the above figures, a symbol $\leftrightarrow$ denotes amplitude of fluctuating cavitation

It is significant that the curve of τ_{cz} is analogous to the shape of pressure distribution curve on a blade surface in case of no cavitation. As the flow-coefficient decreases, the cavitation zone parameter τ_{cz} increases and the maximum point of τ_{cz} shifts to the blade leading edge. But the shape of τ_{cz} curve should be distinguished from that of the pressure distribution in the strict sense, because the

Fig. 13 Test result of cavitation zone parameter τ_{cz} on various blade sections of impeller CY1
Notice: In the above figure, a symbol $\leftrightarrow$ denotes amplitude of fluctuating cavitation

Fig. 14 Test results of cavitation zone parameter τ_{cz} on various blade sections of impeller NA1
Notice: In the above figures, a symbol $\leftrightarrow$ denotes amplitude of fluctuating cavitation

cavitation does not vanish until the pressure gets to the vapor pressure, and the pressure at trailing edge of cavitation zone usually fluctuates in a pump. The cavitation zones of small τ_{cz} near the leading edge in Fig. 12 (a), (b) and Fig. 14(a) correspond to the cavitation zone K_2 which does not occur at smaller flow coefficient than the normal conditions. The position of the rear end of cavitation zone fluctuates usually. The fluctuation is remarkable at flow coefficient $\phi_a=0.16$, when the flow separation may occurs. It is shown by Fig. 12 (b) that the impeller CY1 with larger l/t has smaller values than the impeller G1 and has slow gradient of the curve of cavitation zone parameter τ_{cz} at the optimum flow-rate.

The impeller NA1 with the blade section of NACA-16 series aerofoil, and with the same solidity as the impeller CY1, has smaller τ_{cz} and slow gradient of the curve as shown in Fig. 14 (b).

As the result in Chapter 5, it is shown here that the impeller NA1 has better suction performance than the impellers G1 and CY1. Therefore it may be recognized that the selections of the

solidity and the blade section of the impeller NA 1 are most suitable.

7. Conclusions

Three axial-flow pump impellers were tested to study the overall performances and suction performances, and to visualize their cavitation zone inside each impeller. The following conclusions are obtained from this study.

(1) The head rise ratio under the cavitation condition to that under the non-cavitation condition is expressed as a function of the variable $\tau_a(l/t)_a$ for each test impeller taking the flow coefficient as a parameter, i. e. the effect of solidity is clarified in the range of $(l/t)_a$ from 0.6 to 1.0.

(2) The suction performance depends largely upon the shape of blade section. The impeller with "laminar profile", for example, NACA-16 series, exhibits smaller cavitation numbers for the inception and breakdown points at various flow coefficients. The additional head loss due to cavitation is expressed as a function of the variable $\tau_a(l/t)_a$ for various flow-coefficients, and that of the impeller with "laminar profile" does not increase up to smaller $\tau_a(l/t)_a$. It is therefore recognized that the impeller with "laminar profile" has better suction performance.

(3) The distribution of cavitation zone parameter τ_{cz} on the blade chord, which is analogous to the pressure distribution on the blade surface in non-cavitation condition, is experimentally obtained.

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