Improvement of Pump Performance and Suppression of Cavitation in a Centrifugal Pump by J-Groove

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Abstract

The purpose of the present study is not only to develop a simple method to improve pump performance but also to suppress the occurrence of cavitation in the centrifugal pump by use of J-Groove. J-Groove is a shallow groove installed on the casing wall in the meridional direction. The application of J-Groove to a centrifugal pump with a new type impeller of "semi-closed impeller" has proved its effectiveness as a useful countermeasure of the unstable pump performance and cavitation. The results show that the combination of semi-closed impeller and J-Groove is applied successfully and improves both the pump performance and suction performance.

Introduction

Cavitation phenomenon is a main obstacle in developing a high speed pump. Cavitation causes not only performance drop by passage blockage in an impeller but also damages on the blade surfaces of the impeller, and a bad operating condition leads to driving instability (Ref 1).
While, one of the present authors (Ref 2-5) have proposed shallow grooves, named "J-Groove", mounted on a casing wall of turbomachinery in the meridional direction as a countermeasure to various undesirable flow phenomena such as rotating stall in parallel-walled vaned and vaneless diffusers, and rising head curve with an increase of flow rate in mixed and axial flow pumps.
From the previous related studies, it has been verified that J-Groove has a characteric of suppressing various undesirable flow phenomena by controlling the angular momentum of main flow. In addition, one more important characteristic of the J-Groove is to increase the pressure in a low pressure region by carrying the high pressure fluid to the low pressure region through the groove. Therefore, if the latter characteristic of increasing the pressure at

the low pressure region is applied to the control of cavitation in a centrifugal pump, pump suction performance might be improved.
Since cavitation in an inducer, which is usually operated under the most severe cavitation condition, has been already suppressed by J-Groove (Ref 6), it is considered that suppression of the cavitations in an axial and a mixed flow pumps is possible. However, as J-Groove has been applied to the casing wall of turbomachinery, its effect is limited only to a semi-open impeller so far, and a closed type centrifugal impeller could not be adopted for the use of J-Groove.
Thus, the purpose of this study is to propose a new type "semi-closed impeller" in order to apply J-Groove to the pumps with various type of centrifugal impeller, and then to improve the pump performance and to suppress the occurrence of cavitation, simultaneously, by use of J-Groove.

Experimental apparatus and methods

Test pump and experimental facilities

Performance test and cavitation test of a centrifugal pump are conducted using an experimental apparatus as shown in Fig. 1. Table 1 shows specifications of the pump tested. Specific speed of the pump is n_s=270[m,m^3/min,min^{-1}]. Cavitation test is conducted after having adjusted dissolved oxygen in water to lower than 3 *ppm* by deaeration driving of filtered clean water for 10 hours under lowered internal pressure of the pump and a pressure control tank of capacity 2.5m^3. Available net positive suction head *NPSH* is controlled by base pressure in the pressure control tank which is connected to a vacuum pump. Rotational speed n of the test pump is fixed to 1200 [min^{-1}]. Reynolds number is 2.12x10^6 characterized by radius r and tip speed u_2 of test impeller.

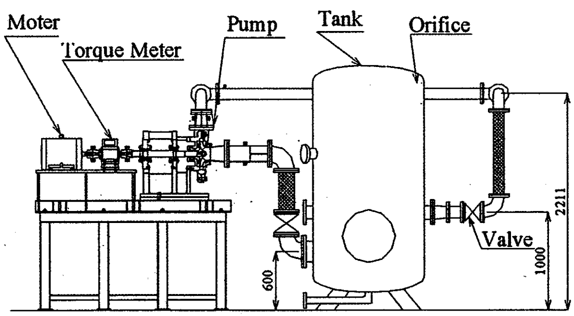


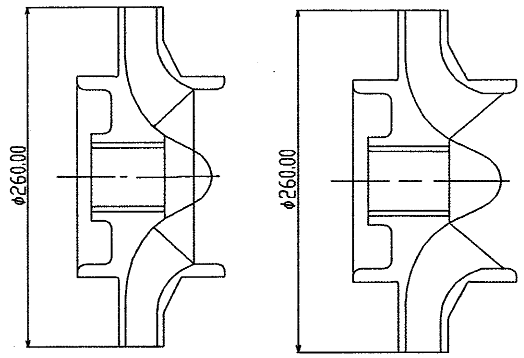
Fig. 1 Test pump and experimental apparatus

Table 1 Specifications of test pump

Specific Speed	n_s=270[m,m^3/min,min^{-1}]
Discharge	Q=1.95[m^{3}min^{-1}], ϕ=0.0946
Total Head	H=11.4[m], ψ=0.856
Rotational Speed	n=1200[min^{-1}]
Reynolds Number	Re=2.12 × 10^6
ϕ:discharge coefficient, ψ:head coefficient	

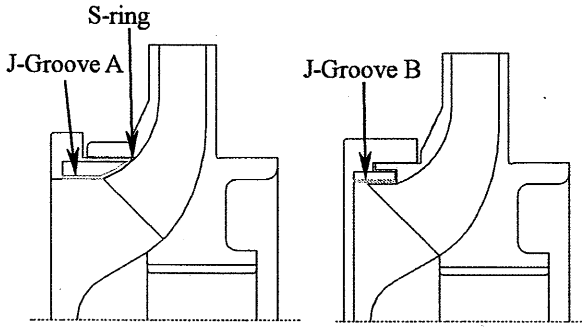
Test impeller

The original impeller tested has very high efficiency and very high suction performance, but it has an unstable head-capacity curve in the very low flow range. To improve both the pump efficiency and the suction performance, together with the improvement of unstable head curve, the original impeller is modified so as to apply J-Groove.
Figures 2 and 3 show test impellers. Test impellers are separated distinctively in two types, closed type and "semi-closed type", by the shape of impeller inlet. Figure 2(a) and 2(b) show



(a) Closed impeller I.C (b) Closed impeller II.C

Fig. 2 Closed type test impellers



(a) Semi-closed impeller I.S with J-Groove A (b) Semi-closed impeller II.S with J-Groove B

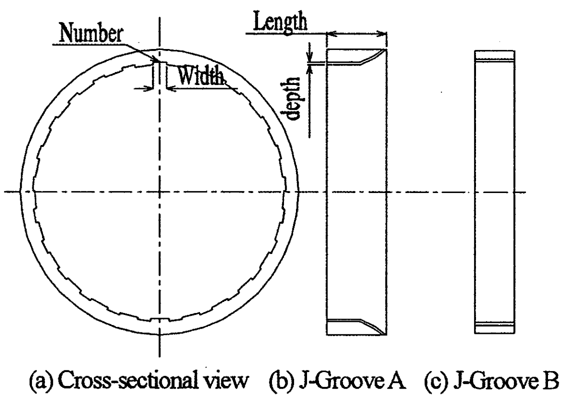
Fig. 3 Semi-closed type test impellers with J-Groove

a normal closed type impeller I.C (original impeller) and a modified closed impeller II.C which is revised from impeller I.C. The closed impeller II.C is designed to improve suction performance in the high flow range by enlarging blade inlet angle and extending blade inlet more to the upstream.

As the J-Groove mounted on a casing wall is effective only for the open type impeller because of its geometry, a new type impeller, which is named a "semi-closed impeller", is proposed in this study in order to improve pump performance and suction performance by use of J-Groove. Front shroud of the impeller at blade inlet area is removed to install J-Groove by enlarging the inlet diameter of front shroud as shown in Figs. 3(a) and 3(b).

Excepting for the configuration of the impeller inlet, the semi-closed impellers of I.S and II.S have same dimensions as that of the closed impellers I.C and II.C, respectively. Moreover, in the case of the impeller I.S, a stopper ring, which is named "S-ring" in this study, is adopted on the blade edge of the impeller inlet as shown in Fig. 3(a). The S-ring is a circular small bump which can block up leakage flow entering directly into the impeller channel.

Configurations of J-Groove



(a) Cross-sectional view (b) J-Groove A (c) J-Groove B

Fig. 4 Schematic view of J-Groove

Table 2 Specifications of J-Grooves

J-Groove	A	B	C	D
Number	25	32	64	32
Width [mm]	7	7	5.6	12
Depth [mm]	1.2	1.5	1.5	1.5
Length [mm]	32.4	20.0	20.0	20.0
Ratio of cross-sectional area	0.0150	0.0238	0.0381	0.0408

Usually, minimum pressure region in the centrifugal pump is located on the blade suction side of the impeller inlet. Therefore, J-Groove with rectangular cross-section is installed along the casing wall near the impeller inlet region including the minimum pressure region as shown in Fig. 3.

The parameters representing the J-Groove configuration are shown in Fig. 4 and Table 2. Four kinds of test J-Grooves are adopted for the experiment. J-Groove A (J_A) is only used for impeller I.S. J-Grooves B to D are used for impeller II.S with same groove depth 1.5mm and length 20mm but groove number and width are varied to examine the effect of dimensions. The ratio of cross-sectional area, which means ratio of cross-sectional areas of J-Groove to the impeller inlet area, in Table 3 is an indicator to assess the effectiveness of each J-Groove tested.

Results and discussions

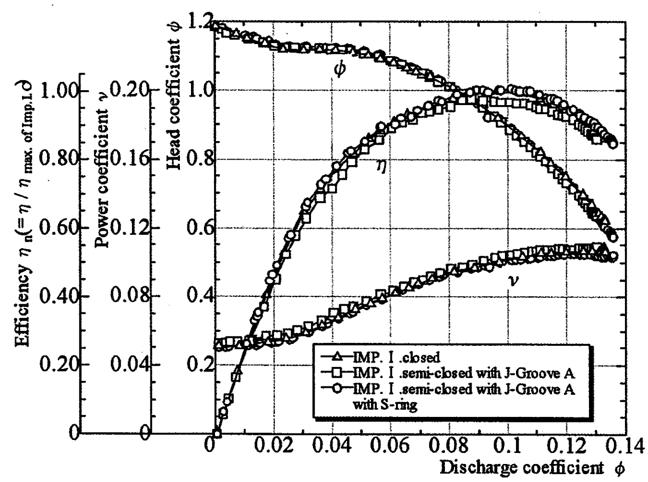
Pump performance

Figure 5 shows performance curves of the test pump for non-cavitating flow condition. Abscissa represents discharge coefficient ϕ and ordinate indicates normalized efficiency $\eta_n (=\eta/\eta_{max.\ of\ Imp.I.C})$, power coefficient ν and head coefficient ψ.

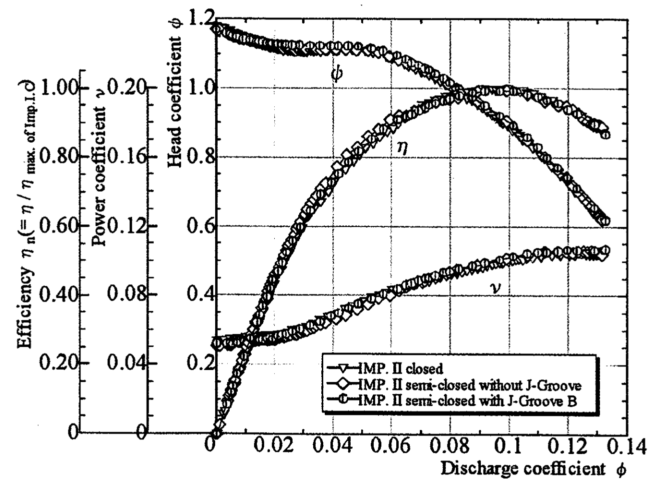
Figure 5(a) reveals that the original impeller, "Imp. I.C", has a performance instability in the range of ϕ=0.02-0.04, which is characterized by an increasing head-capacity curve.

The pump efficiency in the case of semi-closed impeller I.S with J-Groove A drops about 2% at the best efficiency point. However, the lowered efficiency is recovered and exceeds the efficiency of the original impeller I.C by 0.6% with adopting J-Groove A and S-ring. This result suggests that the efficiency might be improved more by the optimization of semi-closed impeller and J-Groove configuration.

Figure 5(b) shows performance



(a) Impeller I

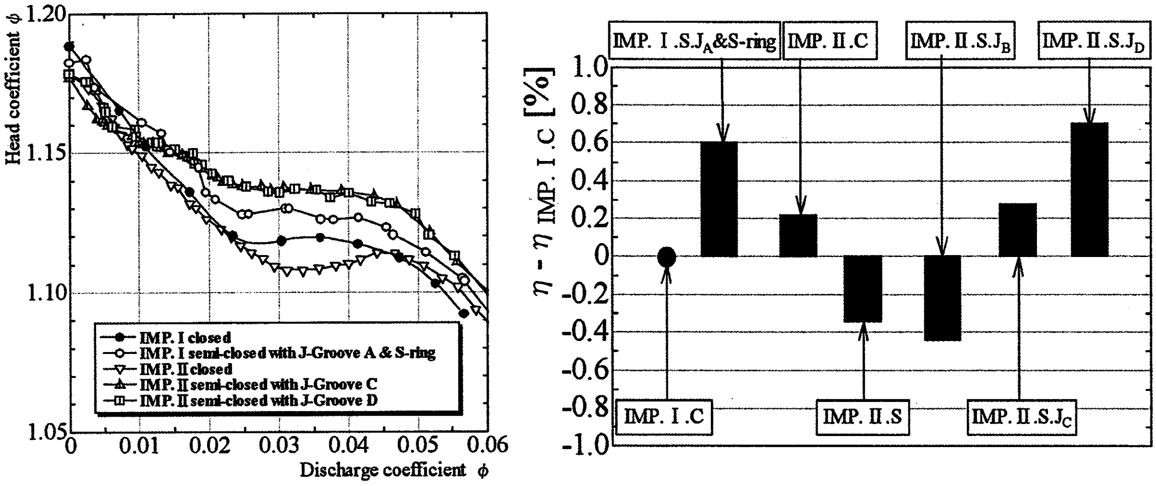


(b) Impeller II

Fig. 5 Comparison of pump performance

curves of the test pump when test impeller II is adopted.

Improvement of pump performance by J-Groove



(a) Improvement of Head curve (b) Comparison of maximum efficiency

Fig. 6 Improvement of pump performance by optimization of J-Groove

Since Figure 5 has shown that J-Groove is effective for the improvement of pump efficiency, optimization of J-Groove configuration and its matching with the semi-closed impeller are examined to obtain the stable operation with high efficiency.

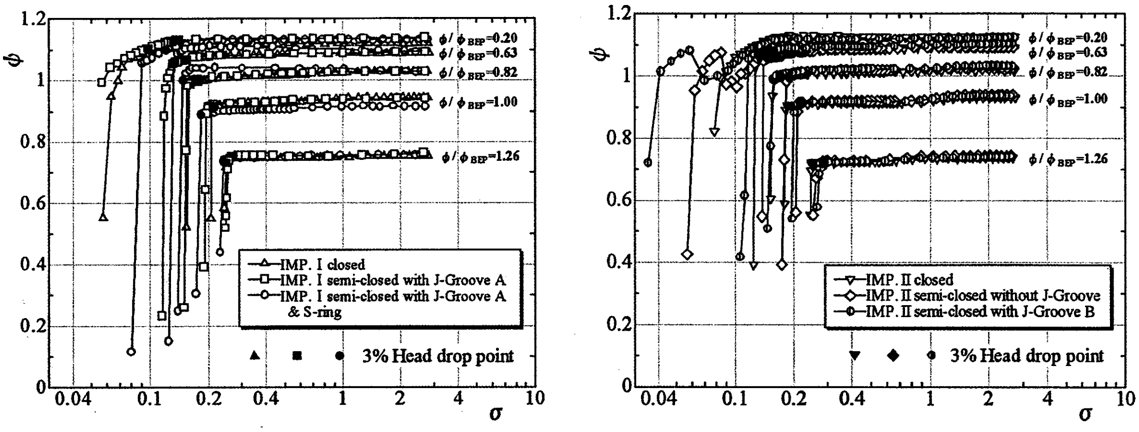
Figure 6 shows the comparison of improved head curves and pump efficiency by semi-closed impellers and J-Grooves from the test for non-cavitating flow condition. Head coefficient ψ of semi-closed impeller I.C is increased clearly at the low flow rate of ϕ=0.02-0.04 by adopting the semi-closed impeller I.S with J-Groove A and S-ring. The unstable head curve disappeared perfectly in the semi-closed impeller II.S with J-Grooves C and D at the partial flow rate, at which performance instability occurs in the case of closed impeller II.C (see Fig. 6(a)). Moreover, pump efficiency at the best efficiency point increases 0.6% by the impeller I.S with J-Groove A and S-ring, and 0.7% by the semi-closed impeller II.S with J-Groove D compared with the original impeller I.C as shown in Fig. 6(b).

From the above result, recovery of head curve and efficiency increase can be achieved by adopting J-Groove, and the effectiveness of the J-Groove is related to the ratio of cross-sectional area of J-Groove to impeller inlet as indicated in Table 2. Therefore, the result suggests that increased cross-sectional area and number of J-Groove rise the maximum efficiency and make the unstable head curve disappear over the whole operating range.

Suction performance

Figure 7 shows comparison of the suction performance of the test pump. Suction performance is examined using cavitation number σ, calculated as follows:

$$NPSH = (p_s - p_v)/\rho g + v_s^2/2g \qquad (1)$$



(a) Impeller I (b) Impeller II

Fig. 7 Comparison of suction performance

$$\sigma = {NPSH}\Big/{u_1^2/2g} \tag{2}$$

where $NPSH$, p_s, p_v, v_s and u_1 represent the net positive suction head, static pressure, vapor pressure, averaged fluid velocity and impeller tangential velocity at the pump inlet.

Figure 7(a) shows the comparison of suction performance by the impeller I. In comparison with the closed impeller I.C, semi-closed impeller I.S only and with S-ring show lower σ at 3% head drop point for the flow rate of $\phi/\phi_{bep} \geq 0.63$.

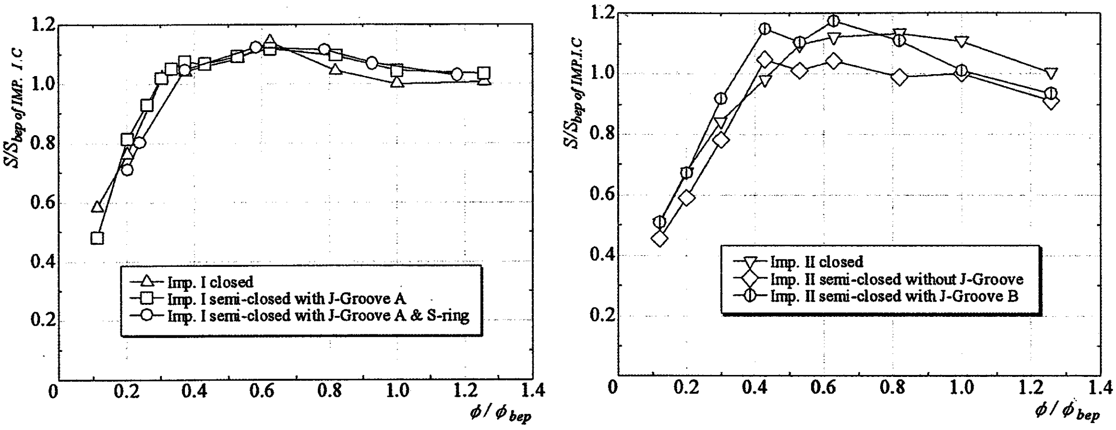
While, Fig. 7(b) represents suction performance by the impeller II. By adopting semi-closed impeller II.S only or with J-Groove B, 3% head drop point moves to higher σ range compared with closed impeller II.C in the almost whole flow rate range. However, at the flow rate of $\phi/\phi_{bep} = 0.20$, an irregular behavior is observed in Fig. 7(b), and head curve has a concave. If the lowered head of semi-closed impeller II.S in the range of $0.06 < \sigma < 0.15$ can be improved, considerable extension of σ to lower range is expected.

In order to compare the suction performance, the suction specific speed S defined as follows is used.

$$S = n\sqrt{Q}/(NPSH_R)^{3/4} \tag{3}$$

Usually, suction specific speed is defined at the best efficiency point but, for the comparison of suction performance of the test impellers with J-Grooves, local $NPSH_R$, determined by $NPSH$ at 3% head drop point for each flow rate, has been used for the definition of local suction specific speed.

The results are compared in Fig. 8 using the relative improvement of S as expressed by $S/S_{bep\ of\ Imp.I.C}$. Though it has been known that the effect of J-Groove for suppressing cavitation can be maximum at the range of partial flow rates according to the previous study (Ref. 6), suction specific speed in the case of semi-closed impeller I.S with J-Groove A is almost same as that of closed impeller I.C at the partial flow rate ranges as shown in Fig. 8(a). Moreover, at the flow rate of $\phi/\phi_{bep} \geq 0.8$, the specific speed in the case of semi-closed impeller I.S with J-Groove A only or with J-Groove A and S-ring improves more than that of the closed impeller I.C.



(a) Impeller I (b) Impeller II

Fig. 8 Comparison of suction specific speed

Figure 8(b) shows comparison of suction specific speed with impellers II.C, and II.S with or without J-Groove B. By installing J-Groove B with semi-closed impeller II.S, suction specific speed improves in the range of $0.2 < \phi/\phi_{bep} < 0.7$, but become lower than that of closed impeller II.C at the best efficiency point and high flow rate.

Improvement of suction performance by J-Groove

Since Figs. 7 and 8 have shown that J-Groove is effective for suppression of cavitation in the semi-closed impeller at partial flow rates, the influence of J-Groove configuration is examined to improve suction performance.

Figure 9 shows the improvement of suction specific speed, expressed as percent increment from that of original impeller I.C. The results show that semi-closed impeller I.S with J-Groove A and S-ring improves suction specific speed in the flow rate range of $\phi/\phi_{bep} \geq 0.5$. Moreover, the combination of semi-closed impeller II.S with J-Grooves C or D shows improvement of suction specific speed near the best efficiency point. Especially, in the case of semi-closed impeller II.S with J-Groove C, suction specific speed increases at the range of almost whole flow rates except for the very low flow rate ($\phi/\phi_{bep} < 0.3$) and high flow rate ($\phi/\phi_{bep} \geq 1.2$).

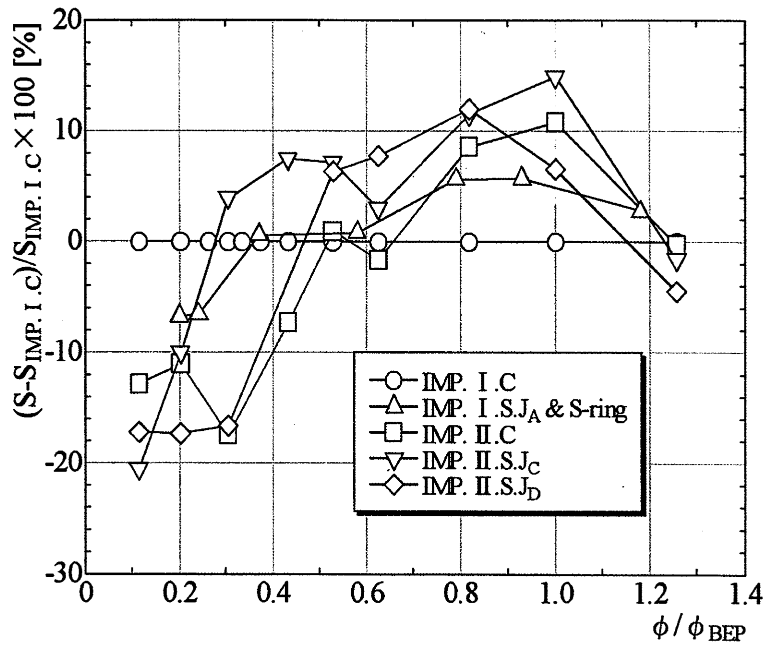


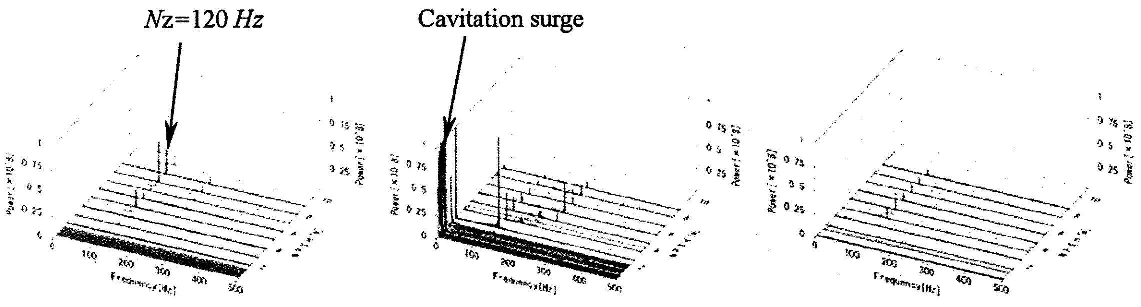
Fig. 9 Improvement of suction specific speed by J-Groove

Suppression of cavitation by J-Groove

In order to investigate the effect of J-Groove on the suppression of cavitation instabilities, spectral analysis of the pressure fluctuation measured at pump inlet is carried out in the cases of closed impeller I.C, closed impeller II.C and semi-closed impeller II.S with J-Groove C as shown in Figs. 10 (ϕ / ϕ_{bep} = 0.43) and 11 (ϕ / ϕ_{bep} = 1.00). Each axis of the graph represents frequency, *NPSH* and power spectrum of pressure pulsation. Blade passing frequency of impeller is *Nz*=120*Hz*.

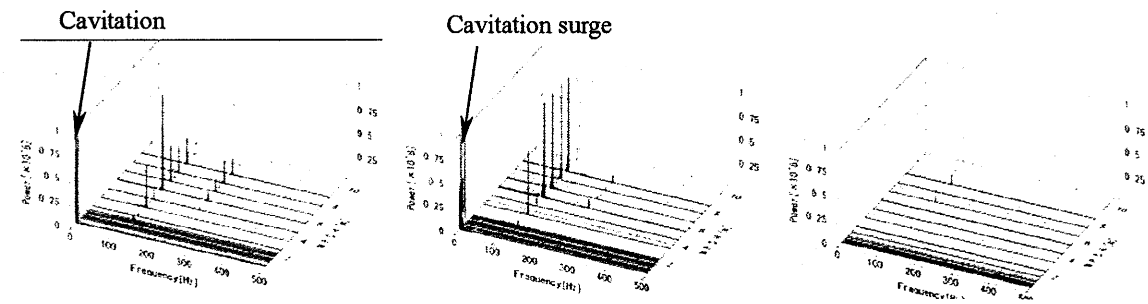
In the case of closed impeller II.C, at the flow rate of ϕ / ϕ_{bep} = 0.43, low frequency pressure pulsation by cavitation surge occurs near the 3% head drop point as shown in Fig. 10(b). The cavitation surge causes periodic vibration in the pump system with cavitation. However, the cavitation surge can be suppressed completely by adopting the semi-closed impeller II.S with J-Groove C as shown in Fig. 10(c)

At the flow rate of ϕ / ϕ_{bep} = 1.00, even though the pressure pulsation with low frequency caused by cavitation and cavitation surge occurs at the *NPSH* range below 3% head drop point in the cases of closed impellers I.C and II.C, respectively as shown in Figs. 11(a) and 11(b), the cavitation instability can be suppressed clearly by installation of semi-closed impeller II.S with J-Groove C.



(a) Closed impeller I.C (b) Closed Impeller II.C (c) Semi-closed impeller II.S with J-Groove C

Fig. 10 Suppression of cavitation by J-Groove (ϕ/ϕ_{bep} = 0.43)



(a) Closed impeller I.C (b) Closed Impeller II.C (c) Semi-closed impeller II.S with J-Groove C

Fig. 11 Suppression of cavitation by J-Groove (ϕ/ϕ_{bep} = 1.00)

Conclusions

In order to further improve efficiency and suction performance of the normal specific speed pump which has high efficiency and high suction performance, newly designed semi-closed impeller is proposed and the effect of J-Groove is investigated experimentally. The results are summarized as below.

1. Pump performance and suction specific speed can be improved simultaneously by adopting semi-closed impeller with optimum J-Groove. The effect is considerable in the range near the best efficiency point.
2. Pump efficiency can be improved apparently by the effect of Stopper ring installed in the semi-closed impeller with J-Groove. The stopper ring blocks up leakage flow at impeller inlet.
3. Unstable head curve at low flow range disappeared completely by adopting semi-closed impeller and J-Groove. Moreover, cavitation surge occurring in the partial flow range and cavitation occurring at the whole flow range can be also suppressed by adopting the semi-closed impeller and J-Groove.

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