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Theoretical Head of Semi-Open Impeller

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Abstract: *Pumping head of semi-open impeller is known to drop rapidly with an increase of tip clearance. This head drop has long been treated as the result of increase of hydraulic loss in an impeller channel due to leakage through tip clearance. The present paper reveals that the head drop is mainly caused by a rapid drop of theoretical head due to recirculation flow existing at the impeller outlet. The PIV measurement and CFD calculation of a very low specific speed impeller flow show that the recirculation flow brings low angular momentum into the impeller channel through tip clearance and decreases both the pumping head and the shaft power.*

Keywords: ***Theoretical Head, Centrifugal Impeller, Tip Clearance, Recirculation Flow, PIV, CFD, Very Low Specific Speed***

1. Introduction

The efficiency of semi-open impeller is known to drop rapidly with an increase of tip clearance. Not only the efficiency but also the pumping head and discharge at the best efficiency point decreases sharply with an increase of tip clearance (Pfleiderer, 1961, Murakami, 1976, Engeda, 1987, Uno, 1990). This head drop has long been treated as the result of increase of hydraulic loss in the impeller channel due to a leakage through a tip clearance. Thus, the loss mechanism caused by the tip clearance flow has long been the target of research to be clarified in the steady problems of semi-open type impeller, especially in the mixed flow and axial flow turbomachines (Rains, 1954, Hesselgreaves, 1969).

The present authors have long made extensive studies on the performance characteristics of a very low specific speed pump (Kurokawa, 1998, 2000), as the pump efficiency drops sharply with a decrease of specific speed. The width of impeller channel of very low specific speed pump becomes too narrow to manufacture, and a semi-open type is necessarily used. In this case, the ratio of tip clearance to the impeller outlet width becomes extraordinary large, and the influence of tip clearance also becomes relatively large compared with the ordinary specific speed impeller. Thus a very low specific speed impeller is quite appropriate to determine the influence of tip clearance flow on the performance characteristics

The present study is aimed to reveal the influence of tip clearance flow on the pumping head, the shaft power and the efficiency quantitatively in a semi-open impeller, and the relation between performance characteristics and tip clearance flow is analyzed by use of PIV measurement of pump internal flow together with the commercial CFD code. The new flow model applicable for analyzing the performance of a semi-open or an open impeller is presented and discussed.

2. Experimental Apparatus

Three kinds of centrifugal impeller of very low specific speed, $n_{SQ} = 57.5\,[m,\ m^3/min,\ rpm]$, were tested in the same volute casing. The schematic view and the dimension of impellers are shown in Fig.1 and Table 1. All of the impellers tested have the same inlet and outlet radii, r_1, r_2, and the same inlet and outlet angles, β_1, β_2, which were proved to have the highest efficiency in the very low specific speed range (Kurokawa, 2000). Impeller A of closed type and Impeller B of semi-open type have the same configuration but for the front shroud, and Impeller C has much larger outlet width of $b_2 = 8mm$ compared with the Imps. A and B of $b_2 = 2mm$.

To measure the impeller outlet flow by LDV, the front casing is made of acrylic resin and the outer diameter of Imps. B and C was cut by 20 mm (Imp. B', C') so as to make the measurements by Laser light beam possible.

In order to know the details of flow field of very low specific speed impeller, another pump apparatus was used and PIV method was applied. The impeller and the casing were made of acrylic resin and the double-pulsed Laser sheet of 0.5 mm in thickness was lead into the impeller passage from the direction tangential to the shaft. The radial vane impeller of which specific speed is $100\,[m,\ m^3/min,\ rpm]$ was used to visualize the flow in the impeller channel of the outlet width $b_2 = 8mm$ and the tip clearance $c = 1mm$.

Test impeller	A	B	C
Type	Closed	Semi-open	Semi-open
z	6		
$t\,[mm]$	4		
$b_1\,[mm]$	10		15.4
$b_2\,[mm]$	2		8
$r_2\,[mm]$	101		
β_1 [deg.]	20.5		
β_2 [deg.]	60		
n_{SQ}	57.5		-

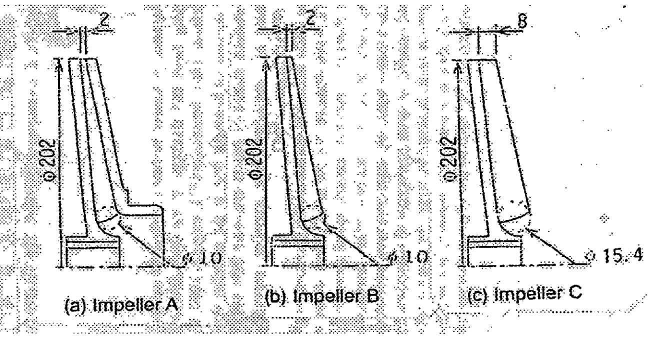


Fig.1 Configuration and dimension of very low specific speed impellers tested

3. Experimental Results and Discussions

3.1 Performance characteristics of semi-open impeller

The characteristic curve of the test pump is shown in Fig. 2, where η, ψ and ν are efficiency, head coefficient and shaft power coefficient, respectively, and the abscissa ϕ is the discharge coefficient. The performance curves of closed impeller (Imp. A) are compared with those of semi-open impeller (Imp. B) together with the theoretical head calculated from Wisner formula.

According to the conventional treatment, a semi-open impeller has many advantages compared with a closed impeller, such that the disk friction is half of that of a closed impeller and the leakage from discharge to suction through a front wearing ring is zero.

Figure 2 clearly reveals that a semi-open impeller has much lower efficiency than a closed impeller, and that this is mainly due to a remarkable drop of pumping head. This rapid head drop has long been treated as an increase of hydraulic loss $H_l = H_{th} - H$ caused by the leakage in the tip clearance. As an efficiency of a semi-open impeller is known to come close to that of a closed impeller with a decrease of tip clearance, the head curve of a semi-open impeller should come near to that of a closed impeller.

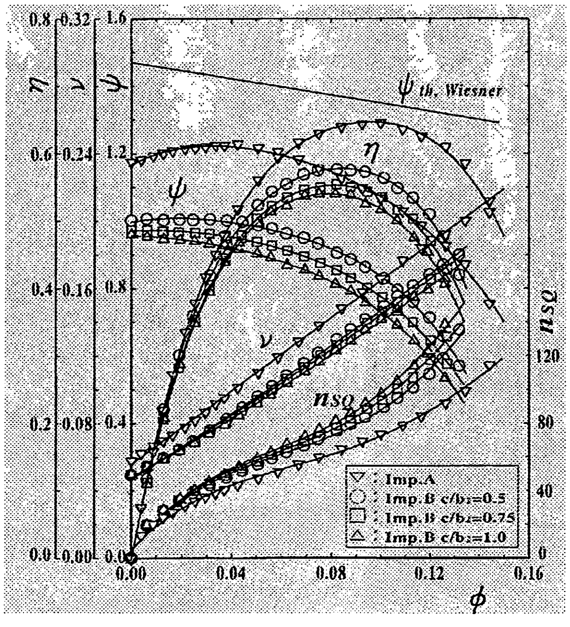


Fig. 2 Performance characteristics of impellers ($\psi_{th,Wiesner}$:calculated by use of Wiesner formula)

However, the head curve does not come near to that of a closed impeller, even if the gap is reduced to zero as shown in Fig. 2. This implies that the conventional treatment that the theoretical head is same both in a closed impeller and a semi-open impeller is contradictory to the present results.

Thinking that the shut-off power is mainly occupied by the disk friction power, Figure 2 also reveals that the disk friction of a semi-open impeller is not half of that of a closed impeller. A relatively small difference of shut-off power between a closed impeller and a semi-open impeller shows that there exists another friction power in the front gap of a semi-open impeller.

To summarize the above results, there arises two problems contradictory to the present experimental results in the conventional treatment, that is, the theoretical head and the disk friction of a semi-open impeller.

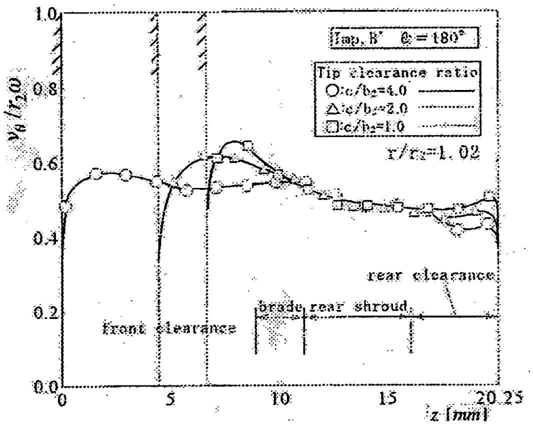


Fig. 3 Tangential velocity at impeller outlet

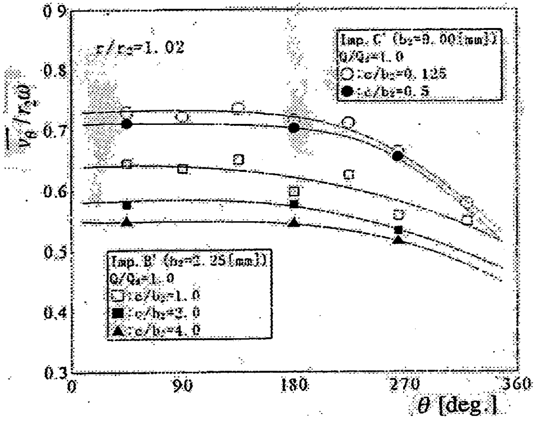


Fig. 4 Variation of $v_{\theta 2}$ around impeller

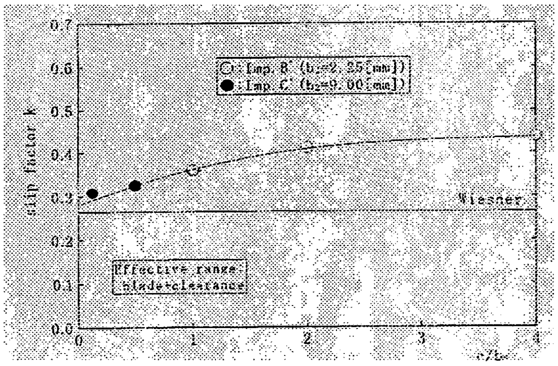


Fig. 5 Slip factor of semi-open impeller

3.2 LDV measurements of outlet flow of semi-open impeller

To determine the reason of the above contradiction, the flow at the outlet of Imp. B was measured by LDV. As the theoretical head in case of no inlet swirl is given by

$$H_{th} = u_2 v_{\theta 2}/g \tag{1}$$

where u_2 and $v_{\theta 2}$ are impeller speed and fluid tangential velocity at the impeller outlet, respectively, the variation of $v_{\theta 2}$ is of key importance to discuss the theoretical head. The measured values of $v_{\theta 2}$ at the impeller outlet $r/r_2 = 1.02$ are plotted in Fig. 3. It is recognized that the tangential velocity is uniform over the section, even though the tip clearance c is much larger than the blade outlet width b_2, and that the tangential velocity is relatively larger in the tip clearance.

To discuss about the dependence of $v_{\theta 2}$ on the tip clearance of a semi-open impeller, the sectional average of the tangential velocity $\overline{v_{\theta 2}}$ is plotted in Fig. 4 against the angle θ measured from the volute tongue. It is recognized that the fluid tangential velocity is largely dependent upon the tip clearance ratio c/b_2, which reveals that the theoretical head of a semi-open impeller is not same as that of a closed impeller and changes with the tip clearance ratio.

The slip factor k is defined as follows:

$$k = (v_{\theta 2\infty} - \overline{\overline{v_{\theta 2}}})/u_2 \tag{2}$$

where $v_{\theta 2\infty}$ and $\overline{\overline{v_{\theta 2}}}$ are tangential velocity in case of infinite blade number and mass-averaged tangential velocity, respectively. As it is difficult to measure the radial velocity component with sufficient accuracy because of a very small value in a low specific speed impeller, the section-averaged $\overline{v_{\theta 2}}$ at the best efficiency point is used to obtain the slip factor, which is plotted against the tip clearance ratio c/b_2 in Fig. 5. It is seen that the measured values of different impellers come to a line, and that a slip factor come near to the Wiesner formula with a decrease of tip clearance ratio.

The tangential velocity at an impeller outlet is the result of impeller flow, and to reveal the sudden drop of theoretical head of a semi-open impeller, it is necessary to examine the variation of tangential velocity in the impeller channel. Thus the radial pressure distribution in the tip clearance of a semi-open impeller was measured and the "average" tangential velocity component $\overline{v_\theta}$ was estimated from the balance between the pressure gradient and the centrifugal force as follows:

$$dp/dr = \rho\overline{v_\theta}^2/r \qquad \therefore \overline{v_\theta} = \sqrt{\rho(dp/dr)/\rho} \tag{3}$$

Figure 6 shows the change of average tangential velocity thus calculated from the impeller entrance to the exit. The tangential velocity in the tip clearance is not same as that in the impeller channel, but Fig. 6(a) clearly shows that the fluid rotates with nearly the same velocity as the impeller speed, and that it decreases sharply in the range $r/r_2 > 0.8$ toward the impeller outlet to about 70% of $r_2\omega$. However, with an increase of gap ratio c/b_2 the average tangential velocity decreases as shown in Fig.6 (b), the low velocity range spreads to $r/r_2 > 0.7$, and the tangential velocity at the impeller outlet also decreases.

The above result reveals that the tip clearance flow in the outer radii is much different from that in the inner radii, and thus the theoretical head is largely influenced by the tip clearance flow behavior in the outer radii. Then, the problem is why and how the theoretical head depends upon tip clearance.

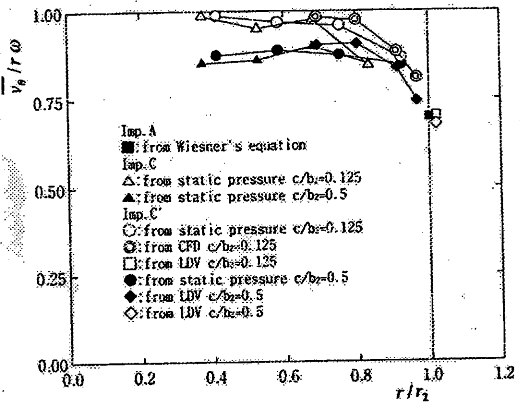
To give the solution, it is necessary to know the details of the velocity field of tip clearance flow, and flow visualization technique by use of PIV and the CFD technique were applied to reveal the behavior of tip clearance flow in a semi-open impeller.

3.3 PTV and CFD in a semi-open impeller

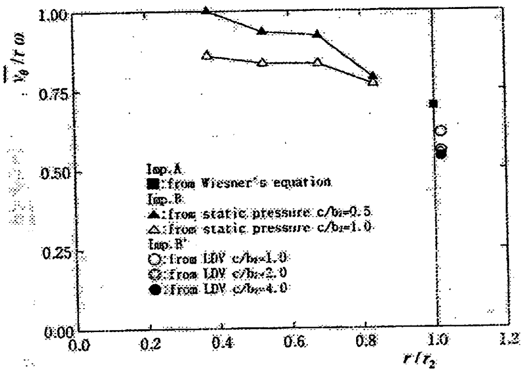
To determine the gap flow characteristics in a semi-open impeller, another pump apparatus to which PIV technique is applicable was used. The test impeller (Imp. D) has six radial vanes. Laser light sheet of 0.5 mm thickness was lead into the impeller channel from the transparent sidewall and the velocity vectors in three layers of impeller channel, $z/b_2 =$ 0.05, 0.50and 0.95 (z : distance from main shroud) were measured.

Comparison of the velocity vector in three layers is shown in Fig. 7. It is recognized that the velocity field is much different from an usual specific speed impeller. In a very low specific speed impeller of a closed type, large separation occurs along the blade pressure side even at the BEP (Kurokawa, 1998). But no separation is observed in Fig. 7, which is due to a strong influence of tip clearance flow. As a strong flow is induced from the pressure side into the suction side through a tip clearance, it brings higher energy fluid from the suction side to the pressure side across the blade channel, and makes separation disappear. Here, it is to be noted from Fig. 7(c) that the mean flow direction is inward in the tip clearance, while it is outward in the middle plane (Fig, 7(b)). It is also to be noted that the velocity vector is much larger near the outer radii than in the other radii, which shows that the tangential velocity of the absolute flow rapidly decreases toward the impeller outlet.

The change of tangential velocity along the blade from inlet

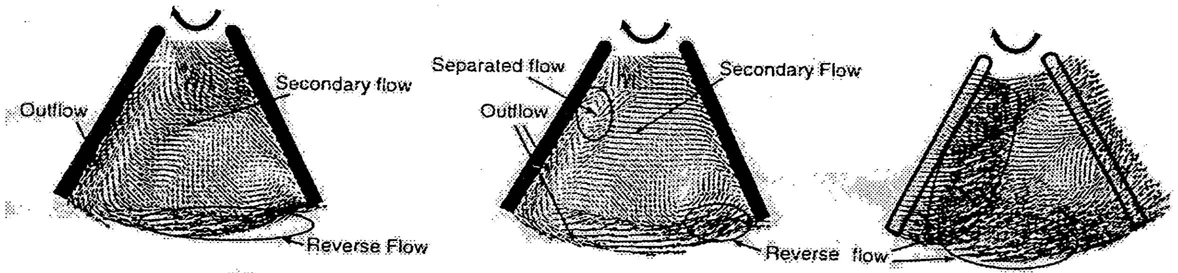


(a) $c/b_2 = 0.125 \sim 0.5$



(b) $c/b_2 = 0.5 \sim 1.0$

Fig.. 6 Tangential velocity in the gap



(a) $z/b = 0.95$ (b) $z/b = 0.5$ (c) $z/b = 0.05$

Fig. 7 Phase averaged relative velocity vectors of Imp. D at BEP

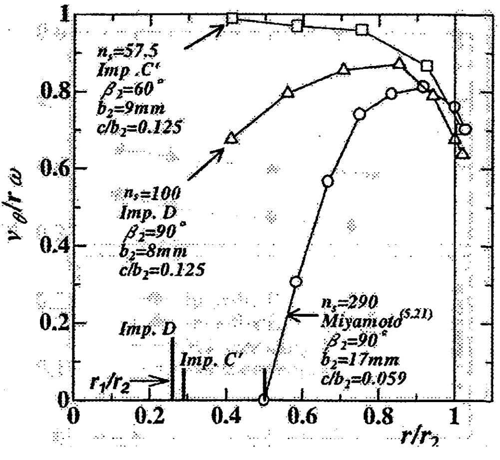


Fig. 8 Tangential velocity in impeller

to outlet is compared in Fig. 8 with those of two impellers of different specific speed. The curve of ordinary specific speed impeller is from the literature (Miyamoto, 1993).

It is recognized from Fig. 8 that the radial variation of fluid tangential velocity v_θ depends largely on the specific speed, but that it is almost same in the outer radii. This reveals that the deceleration process of tangential velocity in the outer radii is same in three semi-open impellers.

Generally speaking, a rapid drop of fluid rotation, or a decrease of angular momentum, is caused by a torque reduction or by mixing with low angular momentum fluid. In this case, there is no torque reduction in the outer radii, so a rapid drop of fluid rotation in the outer radii should be due to the mixing with low angular momentum fluid. The mixing process might be due to the "recirculation flow" coming from impeller outlet into the tip clearance.

Here, it is to be noted in Fig. 8 that the fluid rotational speed of a very low specific speed impeller is surprisingly large over the whole impeller channel when compared with an ordinary specific speed impeller.

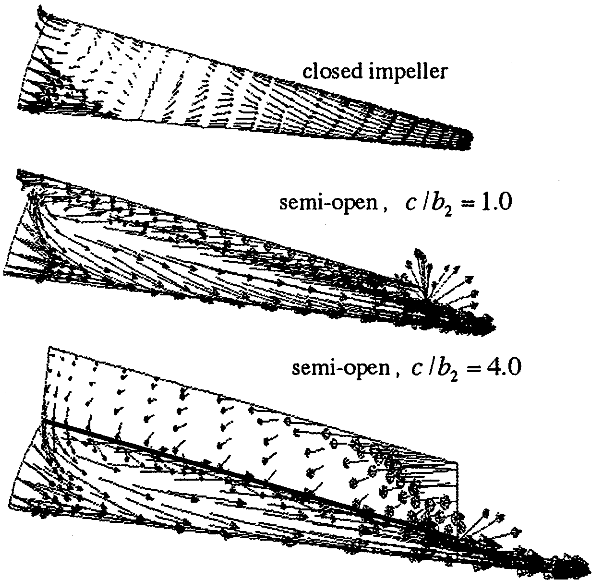


Fig. 9 Cross-sectional view of relative velocity near to suction side (Imp. B', $Q/Q_0 = 1.0$)

In order to determine the influence of tip clearance flow more clearly, the velocity profile of the impeller channel in the axial direction is needed. For this purpose used was the commercial CFD code (Tasc-flow) of which results have been proved to be satisfactory in the accuracy (Choi, 2002).

The velocity vector near the suction side is compared in Fig. 9 for three cases, a closed impeller and two semi-open impellers of different tip clearance ratio. It is recognized that the velocity in a semi-open impeller is much different from that in a closed impeller, especially at the impeller outlet. Detailed examination of the data reveals that this difference is mainly caused by a large difference of flow-rate inside of the impeller channel, though the pump flow rate is same. This means that there exists large recirculation flow in the tip clearance as shown in Fig. 10, and the recirculation flow causes a rapid increase of impeller outlet flow rate resulting a rapid drop of tangential velocity at the impeller outlet, since the tangential velocity at an impeller outlet is given as follows;

$$v_{\theta 2} = (1-k)u_2 - v_{m2}\cot\beta_2/\varepsilon_2 \qquad (4)$$

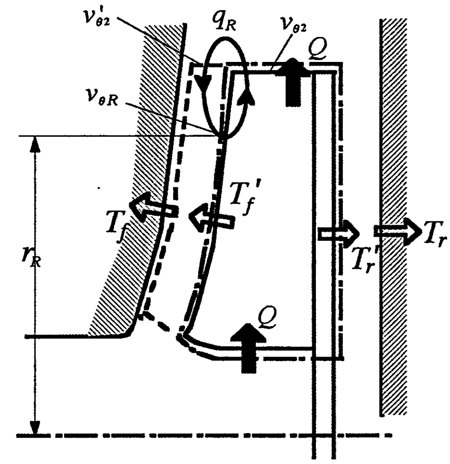


Fig. 10 Flow model of semi-open impeller

where v_{m2} is the meridian velocity and ε_2 is the displacement rate due to blade thickness at impeller outlet. Thus the recirculation flow causes a rapid drop of theoretical head and the increase of slip as shown in Fig. 5 through the increase of impeller flow. Here, it is to be noted that the blade tip leakage from the pressure side to the suction side causes a sudden drop of tangential velocity of impeller absolute flow, but Figure 7 reveals that its influence on $v_{\theta 2}$ is much smaller than that of the recirculation flow.

3.4 New flow model of open and semi-open impellers and theoretical head

A new flow model is proposed so that the theoretical head of a semi-open impeller can be theoretically determined. Considering the angular momentum balance in the control volumes surrounded by the dotted line and the chain-dotted line in Fig. 10, the following equations are deduced:

$$T = \rho(Q+q_R)(v_{\theta 2}r_2 - v_{\theta 1}r_1) + \rho q_R(v_{\theta 2}r_2 - v_{\theta R}r_R) \qquad (5)$$

$$T_F = T_F' + \rho q_R(v_{\theta 2}'r_2 - v_{\theta R}'r_R) \qquad (6)$$

where T, $T_F \equiv T_f + T_r$ *and* $T_F' \equiv T_f' + T_r'$ are the torque transmitted from impeller to fluid, the friction torque of stationary side walls, and the so-called disk friction torque, respectively. q_R is the recirculation flow rate, and $v_{\theta R}$ *and* $v_{\theta 2}'$ are the tangential velocity at $r = r_R$ where the recirculation flow enters into impeller channel and that near the wall at $r = r_2$. Here, T_F' is the friction torque supplied from impeller surface to fluid in the tip clearance, and is difficult to determine in an open or a semi-open impeller, and thus T_F should be used instead of T_F'.

Now, we define the theoretical head of an open or a semi-open impeller as the net head given to through flow;

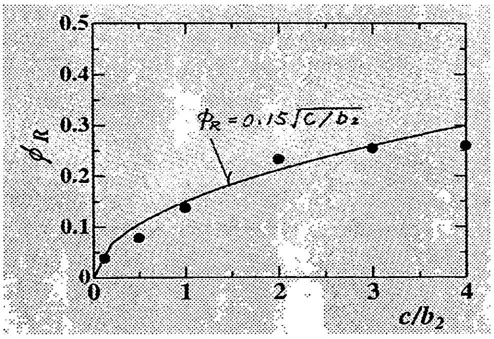
$$\rho g Q[H_{th}]_{open} = T\omega - \rho q_R(u_2 v_{\theta 2} - u_R v_{\theta R}) \qquad (7)$$

Then the theoretical head of an open or a semi-open impeller is expressed in the same way as that of a closed impeller. For the case of no inlet swirl $v_{\theta 1} = 0$ the theoretical head is expressed as

$$[H_{th}]_{open} = u_2[v_{\theta 2}]_{open}/g \qquad [H_{th}]_{close} = u_2[v_{\theta 2}]_{close}/g \qquad (8)$$

where $[v_{\theta 2}]_{open}$ is given supposing that the slip factor k of an open or a semi-open impeller is equal to that of a closed impeller as

$$[v_{\theta 2}]_{open} = [1 - k - (\phi + \phi_R)\cot\beta_2/\varepsilon_2]u_2 \qquad (9)$$



Equation (9) reveals that the increase of slip factor in Fig. 5 of a semi-open impeller is caused by the increase of impeller outlet flow rate, and thus the recirculation flow rate is calculated from Fig. 5 by $\phi_R = \Delta k\varepsilon_2/\cot\beta_2$ as shown in Fig. 11.

Fig. 11 Recirculation flow rate

Using the head coefficient ψ and putting

$$[\psi_{th}]_{close} \equiv 2\{1 - k - (\phi + \phi_q)\cot\beta_2/\varepsilon_2\}$$

Eq. (7) is expressed as;

$$[\psi_{th}]_{open} = [\psi_{th}]_{close} - 2(\phi_R - \phi_q)\cot\beta_2/\varepsilon_2 \qquad (10)$$

where $\phi \equiv Q/A_2u_2$ is the discharge coefficient, $\phi_q \equiv q/A_2u_2$, $\phi_R \equiv q_R/A_2u_2$ (A_2:Impeller outlet sectional area) are those of leakage flow in a closed impeller and recirculation flow in an open or a semi-open impeller. In the above equation the second term of the right side is the decrement of theoretical head due to the increase of impeller outlet flow rate compared with a closed impeller.

The shaft power is calculated by $P = (T + T_F')\omega$, and the shaft power coefficient of an open or a semi-open impeller is thus obtained from Eqs. (5) and (6) as follows:

$$\begin{aligned}[v]_{open} &= 2\{\phi + (1-\alpha)\phi_R\}[v_{\theta 2}]_{open}/u_2 + [v_D]_{open} \\ &= [v]_{close} + \Delta v_F + 2(1-\alpha)(\phi_R[v_{\theta 2}]_{open} - \phi_q[v_{\theta 2}]_{close}) \qquad (11) \\ &\quad - 2\phi(\phi_R - \phi)\cot\beta_2/\varepsilon_2\end{aligned}$$

where $[v]_{close} \equiv [v_F]_{close} + (\phi + \phi_q - \alpha\phi_q)(\psi_{th})_{close}$, $\Delta v_F \equiv [v_F]_{close} - [v_F]_{open}$ and $\alpha \equiv v_{\theta 2}'/v_{\theta 2}$.

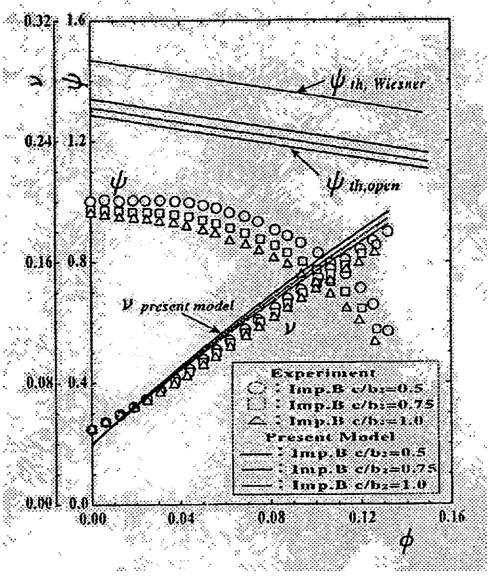


Fig. 12 Comparison of theory

From Eqs. (8), (9) (10) and (11), it is revealed that:

(1) Compared with a closed impeller, an open or a semi-open impeller has much lower theoretical head due to (a) the decrease of tangential velocity caused by recirculation flow rate, and (b) the decrease of angular momentum which recirculation flow takes into the impeller channel.
(2) Recirculation flow of an open or a semi-open impeller behaves like a leakage flow of a closed impeller, but its flow rate is much larger and is given from Fig. 5.
(3) Compared with a closed impeller, the shaft power of an open or a semi-open impeller decreases by the decrement of theoretical head but increases by the power which recirculation flow takes into impeller channel.

In the above equations the value $\alpha \equiv v_{\theta 2}'/v_{\theta 2}$ is determined by assuming the 1/7-th power velocity profile in the casing wall boundary layer at the impeller outlet and $\alpha = 0.83$.

After all the theoretical head and shaft power of an open and a semi-open impellers are theoretically determined by use of the theoretical head of a closed impeller $\psi_{th,Wiesner}$ shown in Fig. 2. The calculated results for theoretical head and shaft power are compared in Fig. 12. It is seen that the calculated shaft power is in good agreement with the present measurements.

4. Conclusion

In order to determine the performance characteristics of an open or a semi-open impeller, the theoretical head and the shaft power are formulated by use of a very low specific speed impeller which has extraordinary large tip clearance ratio. The results obtained are summarized as follows;

(1) Here is proposed a new flow model characteristics of an open or a semi-open impeller. This flow model is characterized by a recirculation flow existing around the impeller outlet.

(2) The recirculation flow behaves like a leakage flow at the back of a closed impeller. But the recirculation flow rate is much larger than the leakage flow rate, and it brings low angular momentum fluid directly into the impeller channel and causes a rapid drop of tangential velocity of the absolute flow at the outer radii. The influence of blade tip leakage is relatively small compared with that of the recirculation flow.

(3) Theoretical head of an open or a semi-open impeller is much lower than that of a closed impeller due to (a) the decrease of tangential velocity caused by recirculation flow rate, and (b) the decrease of angular momentum which recirculation flow takes into the impeller channel.

(4) Compared with a closed impeller, the shaft power of an open or a semi-open impeller decreases by the decrement of theoretical head but increases by the power which recirculation flow takes into impeller channel.

(5) In an open or a semi-open impeller the disk friction torque is too difficult to formulate, and thus the friction torque of the casing wall should be used instead of the disk friction torque.

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