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A Study on the Flow in a Centrifugal Impeller with Passages of Circular-Arc in Meridional Plane*

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The flow in an impeller is affected by the incidence angle. The impellers used in this experiment are of three types; two of which have constant passage height, but one is with an inducer and another is without, and the other has a constant sectional area all the way from inlet to outlet, but without any inducer.

The influence of incidence angle on the flow in the impeller has been measured by the kiel probe and the yaw-meter that rotate with the impeller. From this result, it has been recognized that the separation of the flow occurs at the triangle-area that is bounded by the trailing face of blade and the shroud.

The pressure distribution on the blade face that has been measured in the experiments is compared with that of the two-dimensional theory. This theory is found to be in comparatively good agreement except for the region near the leading edges of the blades with the experimental results; that is, the pressure on the blade face is influenced by the main flow only, and it is hardly affected by the secondary flows that complicate the flow through the impeller.

1. Introduction

In this paper, an influence of incidence angle on the flow in the centrifugal impeller is studied by experiment, and the pressure distribution on the blade faces is measured for comparison with the two dimensional potential theory. In fact, the flow pattern in the region near the inlet of impeller is particularly strongly influenced by the incidence angle. Accordingly when it comes to studying about the flow throughout the impeller, it is necessary that experiments are done with various incidence angles.

Generally, an inducer of the centrifugal impeller with three dimensional vanes extending to the eye has been bent toward the direction of rotation so as to make the fluid flows into the impeller without shock-loss at the design point, and consequently there is more or less shock-loss except the design point. The thorough understanding of such an inlet shock-loss in the centrifugal impellers is important to make better performance. It was supposed that such a study as shown in this paper had not yet been published up to the present, and

so the author made a special test rig and studied on what effect the incidence angles have on the flow in the rotating impeller. Moreover, the pressure distribution on the blade faces in the case where there was no shock-loss of the inflow was measured and compared with the two-dimensional potential theory, and it was found that the theory agreed relatively well with the experiments except in the region near the leading edges of the blades.

2. Test rig and procedure

Fig.1 gives an outside view, and Fig.2 shows a sectional view of the test apparatus. The inlet channel has an axial cascade of adjustable guide vanes. By means of rubber seal, arranged on both

Fig. 1 Outside view of test rig

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ends of the rotating shaft, the total pressures, relative velocities and static pressures can be measured. This pressure transfer device is the same as the method that the author has used in his earlier studies about the flow through the impeller⁽¹⁾⁽²⁾. The impeller has a diameter of 50 cm, and is running at tip speed of about 56 m/sec to 75 m/sec. The flow rates are measured by means of an orifice installed in the discharge pipe, and are varied by a butterfly valve arranged at the end of the long discharge pipe.

First of all, to observe what influence various incidence angles exert on the flow in the impeller, three types of impellers as shown in Fig. 3 are used. Of these three types, the impeller (a) has no inducer, (b) has one, and the passage height of both impellers is constant from inlet to outlet; accordingly the sectional area of the passages is enlarged gradually toward the impeller tip, and at the exit it becomes about two times the inlet; (c) has no inducer and has a constant sectional area of all parts from inlet to outlet, and this is used later again when the pressure distribution along the blade face is measured. All of these impellers are double-shrouded and a range of central point of the passage height forms a line of circular-arc.

The inlet shock-loss of inflow can be changed freely by the adjustable inlet guide vanes in spite of the impeller having an inducer or not. In order to measure the relative velocity, a cylindrical yaw-meter of three holes is used, and to measure the total pressure a kiel probe used; they are shown in Fig. 4. This yaw-meter is long enough to reach from the hub to the shroud, and is able to measure exactly the tangential component of relative velocity at the circular-arc of the passage in meridional plane. Therefore, the measured relative velocity is less so much as the component

of the relative velocity of the passage height direction than the real relative velocity, but this component may be neglected because it is much less than the other components. A kiel probe used to measure the total pressure shows a constant value in a region of $\pm 40^\circ$ to the direction of flow. The measured pressure by these probes as

Fig. 3 Three types of impeller

Fig. 2 Sectional diagram of test blower

Fig. 4 Yaw-meter and kiel probe

shown in Fig. 2 is conducted by the pressure-transfer cells at both ends of the rotating shaft to the stationary manometer tubes.

The yaw-meter is inserted at typical locations of each impeller shown in Fig. 3, and the relative velocity at the points is measured according to the incidence angles and the flow rate change. The typical locations mean the positions near the driving face and the trailing face of the blade as shown in Fig. 3 (a), and the flow condition at these points seems to be most influenced by the incidence angle. In order to study the influence of incidence angles more in detail, the relative velocity and the total pressure distribution are measured for each type of impellers on the cross sections *A-A* and *B-B* as shown in Fig. 3 in the different conditions of various numbers of rotation, flow rates and incidence angles.

About the impeller (c), in order to measure the static pressure distribution along the blade faces, the blade is provided with seven holes, as shown in Fig. 5, on each of three lines which are the circular-arc line of the middle height of the

Fig. 5 Static-pressure tap location on blade face

Fig. 6 Photograph of impeller back

blade, a line of the distance 3 mm from the shroud surface, and a line of the distance 3 mm from the hub surface. The pressure measured at these positions on the blade face is led statically to the manometer, as shown in Fig. 2, by the pressure transfer device arranged at the shaft ends. Fig. 6 is a photograph of the impeller back. In order to compare with the theory, the experiment has been done in the case where the pre-whirl is given to the stream by the inlet guide vanes arranged in the upstream of the impeller, for the purpose of shock-loss prevention.

3. Experimental results and their considerations

3.1 Flow in the impeller

Figs. 7 to 9 are the results of measurements of the relative velocities about the impeller (a). Fig. 7 is of a case where the incidence angle is adjusted according to changes of the flow rate so as to prevent shock-loss. Figs. 8 and 9 are of respective cases where the outlet angles of the inlet guide vanes are constantly 30° and 65° . Inset figures in these figures show changes of the outlet angle of inlet guide vanes, the incidence angle and the inlet relative velocity, that is, they show the flow conditions at the impeller inlet. The chain-lines drawn across the figures give the mean relative velocities. The full lines a, b and c are the results measured at the typical locations on the driving face side of the blade; line a, line b and

Fig. 7 Change of relative velocity at typical location in impeller (a) with changing inlet condition

line c show respective values at 3 mm distance from the shroud surface, the middle of the passage height, and 6.5 mm distance from the hub surface. A dotted-line b shows similarly the values at the middle of passage height.

Fig. 7 shows that the relative velocity at the driving face side of blade is almost equal to the mean value, but at the trailing face side of blade it shows a much higher value than the mean value, when the flow rate is large. This is caused by the fact that the separation occurs in a portion of the passage on the trailing face side of blade from the secondary flow that is described later on, but in general the flow through the impeller is almost uniform. In this experiment, the velocity at the driving face side of blade becomes lowest at the flow rate $0.4 \text{ m}^3/\text{sec}$, but with further decrease of the flow rate, the velocity again increases because as the adjustable inlet guide vanes are restricted in its outlet angle to within 67° , the flow always comes in with the positive incidence angle.

In Fig. 8, the incidence angle is always positive within a limit of the flow rate treated in the experiment, and with decrease of the flow rate, the incidence angle increases; because of this at the driving face side of blade the velocity becomes higher than the mean value, and at the trailing face side of blade the flow pattern shows the similar tendency to Fig. 7 only when the flow rate is large, but with decrease of the flow rate the velocity suddenly falls, and when the flow rate becomes $0.65 \text{ m}^3/\text{sec}$ the eddy zone which occurs by the separation expands to the measuring location.

Fig. 8 Change of relative velocity at typical location in impeller (a) with changing inlet condition

Fig. 9 shows the velocity transit, that is, the incidence angle changes from negative to positive with decrease of the flow rate. When the flow rate is under $0.45 \text{ m}^3/\text{sec}$ the incidence angle is always negative, consequently the flow inclines toward the trailing face side of blade, and seems to be separated on the driving face of blade at the impeller inlet. However, in this experiment, even when the incidence angle is negative, the steady flow is found at the measuring location on the driving face side of blade. The flow rate continues to decrease and when the incidence angle reaches beyond zero, a separated flow occurs on the trailing face of blade, and on the contrary the velocity on the driving face side of blade is increased.

Figs. 10 (1), (2) and (3) show the distribution of total pressure loss in a cross section A-A of the passage of the impeller when the inlet conditions are different. The total pressure loss in the figures is defined as the ratio of the difference between the theoretical "isentropic" and the measured relative total pressure to the inlet total pressure where the theoretical total pressure is

$$p_r = p_0 \left[1 + \left(\frac{k-1}{2} \right) \left(\frac{\omega r}{c_0} \right)^2 \right]^{k/(k-1)}$$

where

c_0 : speed of sound for stagnation conditions in inlet annulus

k : ratio of specific heats

Fig. 9 Change of relative velocity at typical location in impeller (a) with changing inlet condition

p_0 : stagnation pressure in inlet annulus

r : radius

ω : angular velocity

As these figures show, the least area of the total pressure loss is the central portion in the passage cross section, and the largest area is the triangle-area that is bounded by the trailing face of blade and the shroud. It will be found from the relative velocity distribution of the cross section $B-B$ in Fig. 11 that in this area the flow is separated. The sectional area of this impeller is expanded toward the direction of flow and so the velocity decreases, and furthermore the flow is turned; consequently the flow separation occurs in a triangle-area on the trailing face of blade where the velocity gradient is very sharp. About Fig. 10, the loss in the vicinity of the driving face of blade in Fig. 10 (2) and of the trailing face of blade in Fig. 10 (3) is larger than that in Fig. 10 (1); it is owing to the shock-loss at the impeller inlet.

Fig. 12 shows the total pressure loss in a cross

section $A-A$ of the impeller (b). The inducer of this impeller is bent 30° from the direction of rotating axis to the direction of rotation. The experiments have been made on the case where there is no shock-loss.

From these experiments it is found that a large total pressure loss occurs in the zone of the shroud side of the cross section of passage divided by the diagonal line. Such an impeller shows a tendency that the separation occurs on the trailing face of blade, because the flow is bent to the direction of rotating axis by the inducer just after the flow comes in, and beside the passage area of impeller is spread toward the down stream. The greatest loss area is built up from the fluid of low energy that is made by the separation on the inducer surface and by the bend effect from axial to radial direction. This phenomenon appears distinctly as the velocity of inflow increases.

Figs. 13 (1), (2) and (3) show the distribution of total pressure loss in the cross-section $A-A$ of the impeller (c) at the different operations. From

Incidence angle $\epsilon = 0^\circ$
Impeller-tip speed $U = 56.3$ m/sec
Flow rate $q = 1.16$ m³/sec

Incidence angle $\epsilon = -48^\circ$
Impeller-tip speed $U = 56.3$ m/sec
Flow rate $q = 0.88$ m³/sec

Incidence angle $\epsilon = +23^\circ$
Impeller-tip speed $U = 56.3$ m/sec
Flow rate $q = 1.16$ m³/sec

Fig. 10 Total-pressure-loss distribution in cross-section $A-A$ of impeller (a) in Fig. 3

Incidence angle $\epsilon = 0^\circ$
Impeller-tip speed $U = 56.3$ m/sec
Flow rate $q = 1.16$ m³/sec

Fig. 11 Relative velocity distribution in cross-section $B-B$ of impeller (a) in Fig. 3

(1)
Inlet axial velocity $V_a = 26.4$ m/sec
Flow rate $q = 0.86$ m³/sec

(2)
 $V_a = 36$ m/sec $q = 1.18$ m³/sec

Fig. 12 Total-pressure-loss distribution in cross-section $A-A$ of impeller (b) in Fig. 3

these figures it will be found that even if the impeller-tip speed and the flow rate increase when the inflow is without shock, the total pressure loss is almost constant in the circumferential direction, but the fluid of low energy comes together to the area that is bounded by the trailing face of blade and the shroud.

From above results it turns out that there are the secondary flows as shown in Fig. 14 in the cross-section of passage of the impeller with inducer. These secondary flows occur when the flow passes the inducer (solid-lines in Fig. 14) and is bent from axial to radial direction (dotted-lines). In this figure, the solid-lines and the dotted-lines respectively show the direction of secondary flows which occurred by above mentioned two reasons. In addition to these, there is a secondary flow that arises by the pressure difference between the blades. The secondary flow which is occurred by this pressure difference has the same direction on the shroud surface as the secondary flow by the inducer. These secondary flows carry the fluid of low energy to a corner that is bounded by the shroud and the trailing face of blade, and the separation is accel-

erated; the loss of this area becomes more larger.

3.2 Static pressure distribution on the blade faces

As above mentioned, the flow pattern in the rotating impeller is very complicated, accordingly the presumption of the flow through the impeller by the theory is impossible, but about the static pressures along the blade faces, the author thinks that they are influenced by the main flow only, and are hardly affected by the secondary flows. The theory shown here is based on the equation that has been published by Dr. Stanitz in 1952⁽³⁾. The author so transformed the basic equation that it may be possible to apply it to the impeller as shown in Fig. 16, and the boundary conditions at the upstream and the downstream of impeller were determined at the inlet and the outlet of impeller, respectively⁽⁴⁾.

Fig. 14 Directions of secondary flow

Fig. 13 Total-pressure-loss distribution in cross-section A-A of impeller (c) in Fig. 3

Fig. 15 Comparison of experimental and theoretical pressure distribution along blade faces

Fig. 16 Co-ordinate

The following assumption is made for this theory, that is, the flow conditions are uniform across the passage normal to the center line in the passage, consequently the flow varies only along the center line in the passage, and the fluid particles on the impeller are the absolute irrotational motion, and the fluid has no shock loss at the impeller inlet, being nonviscous and incompressible. This paper shows only the result.

$$w_M = \frac{u_T}{R} \sum_{m=1}^{\infty} A_m \frac{m\pi}{\xi_1} \sin \frac{m\pi}{\xi_1} \xi \sinh \frac{m\pi}{\xi_1} \eta + \frac{q}{2\pi r h}$$

$$w_\theta = -\frac{u_T}{R} \left[\sum_{m=1}^{\infty} A_m \frac{m\pi}{\xi_1} \cos \frac{m\pi}{\xi_1} \xi \cosh \frac{m\pi}{\xi_1} \eta + L \left\{ \frac{R \cos \beta}{\sqrt{L^2 - X^2}} - R \cos \beta \right\} + \frac{L \left(\frac{\pi}{2} - L \right)}{\xi_1} \right]$$

$$\xi = \frac{2L}{\sqrt{1-L^2}} \left\{ \tan^{-1} \left(\sqrt{\frac{1+L}{1-L}} \tan \frac{\sin^{-1} X}{2} \right) - \tan^{-1} \sqrt{\frac{1+L}{1-L}} \right\}$$

$$\xi_1 = -\frac{2L}{\sqrt{1-L^2}} \tan^{-1} \sqrt{\frac{1+L}{1-L}}, \quad \eta = \theta$$

where

- h : passage height at distance r from rotating center
- L : $(=l/r_T)$
- l : radius of curvature of center line in passage
- q : flow rate m^3/sec
- R : radius ratio $(=r/r_T)$
- r : radius, distance from rotating center to arbitrary point on center line in passage
- r_T : radius of impeller
- u_T : impeller-tip speed
- w_M : meridional component of relative velocity
- w_θ : tangential component of relative velocity
- X : $(=x/r_T)$
- x : distance measured along rotating axis from impeller inlet
- θ : angle on conic surface (when $\theta = \pm \alpha/2$, it shows position of blades)
- α : angle between blades on conic surface
- β : angle between conic surface and rotating axis

Consequently, the relative velocity of the fluid in the impeller becomes as follows :

$$w = (w_M^2 + w_\theta^2)^{1/2} \dots\dots\dots (1)$$

From the steady-flow energy equation, the pressure in the impeller is given by

$$\frac{p}{p_0} = 1 + \frac{1}{2g} \{ (r\omega)^2 - w^2 - 2\omega r_1(\omega r_1 + w_{\theta 1}) \} \frac{\gamma}{p} \dots\dots\dots (2)$$

where

- p : static pressure
- γ : specific gravity of fluid
- ω : impeller angular velocity
- g : acceleration of gravity

Subscripts

- 0 : stagnation condition in region of uniform flow upstream of impeller
- 1 : impeller inlet

In Eq. (2) $w_{\theta 1}$ is the tangential component of relative velocity at the impeller inlet, and it is equal zero in this comparative experiment.

The calculated values using the Eq. (2) and the measured values are shown in Fig. 15. The measured static pressure distributions in Fig. 15 are plotted in the curves marked "hub", "mean" and "shroud" in Fig. 5. The static pressures on the blade faces are obtained from the measured pressures with corrections for the centrifugal effects of the air in the rotating pressure lines. The curves "a~a", "b~b" and "c~c" in Fig. 15 show the measured pressures on the lines corresponding to the curves "a~a", "b~b" and "c~c" in Fig. 5, respectively. The test condition of this case is the impeller-tip speed 56.3 m/sec, flow rate 0.97 m^3/sec .

As this figure explains, except the region near the impeller inlet, the agreement between theory and experiment is comparatively good. In particular, the calculated pressure distribution on the driving face of blade coincides very closely with the experimental data. On the other hand, the measured pressure distributions at various blade heights on the trailing face of blade do not pile up to a line, and do not coincide well with the calculated value. This fact explains that the separation occurs on the blade face. The experiments produced the same results although the impeller-tip speed or flow rate changed.

4. Conclusion

It has been recognized that in the full shrouded impeller the most total pressure loss occurs at the corner region that is bounded by the trailing face of blade and the shroud. Accordingly, the improvement on the performance of such an impeller seems to depend on reduction of the area having

the lowest energy. The designers ought to take into consideration the boundary layer in the centrifugal impeller in which the flow passes through many tortuous passages from inlet to outlet.

The measured pressure distribution on the blade face of the impeller with passages of circular-arc in meridional plane is compared with the results of the two-dimensional potential theory. This theory is found to be in comparatively good agreement except the region near the impeller inlet with the experimental result.

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