A Study on the Rotating Stall in Vaneless Diffusers of Centrifugal Fans*
(1st Report, Rotational Speeds of Stall Cells, Critical Inlet Flow Angle)

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The rotational speeds of stall cells in vaneless diffusers and critical inlet flow angles for rotating stalls under the condition of no scroll were studied experimentally. Two experimental equations for rotational speeds are derived and a prediction method is presented. The predicted rotational speeds agree well with measured values in the literature. A simple equation for the critical inlet flow angle is derived from the experimental data. This equation is useful for predicting the onset of a rotating stall. In the experiment, a weak velocity fluctuation was found at the position of reverse flow on the diffuser wall just before the rotating stall. It is concluded that reverse flow is the cause of rotating stall in a vaneless diffuser. The conditions of reverse flow layers on the diffuser wall just before a rotating stall are made clear by a numerical analysis. The properties of a fully developed rotating stall are also presented.

Key Words: Unsteady Flow, Fluid Machine Element, Rotating Stall, Vaneless Diffuser, Centrifugal Fan, Rotational Speed of Cell, Critical Inlet Flow Angle

1. Introduction

A rotating stall may occur in the parallel wall vaneless diffuser of a centrifugal fan or a compressor at comparatively high flow rates whereas it does not occur in the impeller itself, and this may be the principal factor which limits the stable operation range of a turbomachine.

Several studies on the rotating stall of a diffuser have been made. Jansen has developed a theory and has pointed out the instability of the reverse flow layer on the diffuser wall(1). Tsurusaki and others have examined the causal relationship between the reverse flow and the rotating stall(2) and have made clear the flow condition of a fully developed rotating stall(3)(4).

Senoo and Kinoshita have proposed a method for predicting the occurrence of a rotating stall(8) and have presented critical inlet flow angles for diffusers with a width ratio $b/r_i \leq 0.13(10)$. Some experimental results on the rotational speed of stall cells, where the velocity is relatively low and the pressure high(9), have been reported. However, an accurate method for predicting the rotational speed has not yet been presented.

The authors have studied experimentally the rotational speed of cells and the critical inlet flow angles for the onset of a rotating stall in the case where no scroll has been coupled with the diffuser. A centrifugal impeller and parallel wall vaneless diffusers with four width ratios have been used.

In this paper, a method for predicting rotational speeds and an experimental equation for the critical inlet flow angle, which is useful over a wide range of $b/r_i$, are presented. The conditions of the reverse flow layers just before a rotating stall are made clear by the numerical analysis based on the method of Ref. (7).

In this experiment, a weak periodic velocity fluctuation has been found at a reverse flow layer on the
diffuser wall just before the rotating stall. The fluctuating flow precedes the rotating stall and it supports Jansen's theory. This may be the first report on the initial fluctuating flow. A fully developed rotating stall has also been measured for comparison with the initial fluctuating flow.

2. Nomenclature

\( b \): width of diffuser
\( \omega \): rotational speed of cells \( [s^{-1}] \)
\( Q \): flow rate \( [m^3/s] \)
\( r \): radius
\( S \): maximum thickness of reverse flow layer
\( t \): time
\( T \): period of fluctuation
\( v \): flow velocity
\( z \): depth from upper wall (suction pipe side) of diffuser
\( a \): flow angle from tangential direction
\( \kappa \): angle between maximum velocity vector and wall streamline
\( \Omega \): non-dimensional rotational speed of cells (Eq. (1))

Subscripts
- \( i \): diffuser inlet
- \( o \): diffuser exit
- \( R \): onset of rotating stall
- \( r \): radial component
- \( \theta \): tangential component

Superscripts
- : value averaged about time and diffuser width

3. Experimental Apparatus

Figure 1 shows the experimental apparatus used in this study. The unshrouded (no front shroud) impeller has 8 blades of constant width. The impeller exit diameter is 171 mm. Each blade of the impeller penetrates the back shroud and the blade width is adjustable. The width of the impeller has been designed as 17 mm and is changed according to the diffuser width. The clearance between the blade tip and the diffuser wall is kept below 0.5 mm. The impeller is driven by a variable speed motor and its rotational speed is measured by a photo transistor type pick up. The speed is kept at 2 200 rpm in this experiment.

A suction pipe is installed above the impeller. The suction pipe consists of a straight pipe about 1 500 mm in length (connected with the diffuser wall), a 180 deg bend with a 655 mm radius of curvature (connected to the 1 500 mm pipe), and a straight pipe about 1 200 mm long (connected to the bend).

A throttle valve (iris type throttle) for adjusting the flow rate is attached to the last straight pipe. A float type flowmeter or an inlet nozzle, according to the flow rate, is connected with the last pipe.

Measuring holes \((P_1~P_6, L_1~L_4)\) in Fig. 2) are provided on the upper wall (suction pipe side) of the diffuser. The axisymmetry of the flow in the diffuser has been confirmed by measurement of the flow velocity.

4. Measurement Techniques and Data Processing

4.1 Measurement of pressure fluctuation

Pressure fluctuations are measured by a calibrated semiconductor type pressure transducer at point P1 (Fig. 2). The block diagram of the measuring system is shown in Fig. 3 (a) . The measured data are analyzed by an FFT program of a microcomputer. The number of stall cells \((\lambda)\) is obtained from the phase difference \((\phi)\) of the pressure waves between points L1 and L2. \(\lambda\) is determined to be the integer which is nearest to \(\phi/(\text{circumferential angle between L1 and L2})\). In the measurement of \(\lambda\), a trigger pulse formed from the pressure signal at L3 is used for the A-D converter. The period of the trigger pulse is the same as that of the pressure signal. The system for the trigger pulse is shown as 2 in Fig. 3 (b). The
rotational speed of the cells $f_r$ is calculated from $f_r = f/\lambda$, where $f$ [Hz] is the fundamental frequency of the fluctuation.

4.2 Measurement of flow velocity

An I type hot wire probe mounted on a traversing unit is used to measure the two-dimensional velocity vector in the plane parallel to the diffuser wall. The probe is inserted into the diffuser perpendicularly to the diffuser wall. The hot wire output is measured twice at the same point by rotating the probe 90 degrees and the velocity vector is obtained\(^{(3)}\). The measuring system is shown in Fig. 3(b). In the measurement of the fluctuating flow at points P1~P6, the pressure signal at L3 or L4 is used as a trigger pulse. Two continuous velocity waves are measured with a sampling period corresponding to about 1/32 of the fundamental period. The measurement is repeated about 60 times and the data having the same phase are averaged. Since the velocity fluctuations are measured with the trigger pulse obtained from the fixed point, the velocity data at each point are equivalent to velocity data measured simultaneously.

For a steady flow, an appropriate number of velocity data are measured with no trigger pulse and averaged.

The velocity fluctuations, measured at points P1~P6 under the condition of rotating stall, are considered to be spatial, circumferential distributions. The values of the stream function are calculated from the spatial velocity distributions of $u_r$ and $u_\theta$, then the streamlines are drawn.

4.3 Measurement of critical inlet flow angle

The velocity components $\bar{u}_r$ and $\bar{u}_\theta$ are measured at P2 ($r/r_v=1.31$) at flow rate $Q'$ just before the rotating stall. The inlet flow angle $\alpha_v$, at $r/r_v=1.0$ is calculated from $\bar{a} (\bar{a} = \tan^{-1}(\bar{u}_\theta/\bar{u}_r))$ by the method of Ref.(12) for a two-dimensional $(r, \theta)$ flow. The wall friction coefficient in the calculation is obtained from Blasius' equation. The critical inlet flow angle $\alpha_v$ at flow rate $Q$ is calculated from $\bar{a}_v = Q/Q' \times \bar{a}_v$ because the difference between $Q$ and $Q'$ is very small.

5. Experimental Results and Discussion

5.1 Condition of occurrence of rotating stall

The variation in the occurrence of a rotating stall according to the diffuser width is shown in Fig. 4. The width $b=17.8$ mm is close to the design width of the impeller. The open circles show the initiation points of the rotating stall when the suction valve is gradually closed toward $Q=0$, and the solid circles show the disappearance points when the valve is opened from $Q=0$. A gap between the initiation and disappearance points is observed and it can also be seen in other experiments\(^{(24)}\).

For $b=17.8$, the initiation flow rate is equal to $1.88 \times 10^{-2}$ m$^3$/s, which is higher than the design flow rate of the impeller ($1.62 \times 10^{-2}$ m$^3$/s). From this point, it is reasonable to assume that the measured pressure fluctuation is not based on the rotating stall of the impeller but is based on that of the diffuser.

The initiation flow rate is considerably lower for a narrower diffuser (Fig. 4). This suggests a causal relationship between the reverse flow on the diffuser wall and the rotating stall because the flow rate for the initiation of the reverse flow is considerably lower for the narrower diffuser.

For $b=9.1$ and 7.1, the rotating stall disappears near $Q=0$, where the frequency of the pressure fluctuation is about 55~82% of the impeller rotational speed [rps]. From this, it is thought that the rotating stall occurs in the impeller itself.

5.2 Flow condition

5.2.1 Local velocity fluctuation just before a rotating stall

In the case of $b=18.1$ mm, a periodic velocity fluctuation has been found at $r/r_v=1.31$ when the flow rate has been gradually decreased to a point about 8%
higher than the initiation point of a rotating stall. The number of cells is one and the rotational speed of the cell is equal to 11.3 [s⁻¹]. A developed rotating stall occurs just after this state (local fluctuation).

Velocity fluctuations have been measured at various points in the diffuser. Figures 5 and 6 show the fluctuations of velocity components $v_r$ and $v_\theta$. The time average velocity is included in Fig. 5 and is omitted in Fig. 6. A reverse flow (the region of $v_r < 0$ in Fig. 5) is observed alternately on the upper wall ($z/b = 0$) or on the lower wall ($z/b = 1$). It is obvious from Fig. 6 that relatively strong fluctuations appear only at $r/r_1 = 1.31$, where the fluctuations are out of phase between the upper and lower walls and a node is observed near $z/b = 0.5$. The fluctuations are very weak at the diffuser exit.

Figures 7(a) and (b) show Lissajous figures for the velocity fluctuations. The radial fluctuation is larger than the tangential one near the upper and lower walls.

From the measurement of the steady flow near this flow rate, a reverse flow is observed at $r/r_1 = 1.31$ on the upper wall (Fig. 13). It is supposed that the axisymmetric reverse flow is changed to a non-axisymmetric one by small disturbances and an outward flow is caused at one point in the circular reverse flow layer. If the non-axisymmetric reverse flow layer rotates, reverse and outward flows appear periodically on the diffuser wall. The fact that a propagating fluctuation occurs at the steady reverse flow layer proves that the reverse flow is unstable and is a cause of the rotating stall.

5.2.2 Developed rotating stall

The flow condition of a fully developed rotating stall is different from that of the above-mentioned local fluctuation. The velocity fluctuation of the rotating stall is observed throughout the diffuser and the phase of the velocity fluctuation becomes roughly uniform along the diffuser width. Figure 8(a) shows the instantaneous streamlines of the rotating stall in the case of two cells. The streamlines are drawn from the velocities averaged along the diffuser width. The pattern in Fig. 8(a) propagates at a constant velocity in the direction of impeller rotation (counterclockwise). The air which enters the diffuser continuously flows along the elliptic streamline. The air which flows out of the diffuser enters the diffuser again at the exit. The streamlines suggest the existence of two clockwise vortices at points G1 and G2.

Figure 8(b) shows the streamlines based on the fluctuating components of the velocity. The streamlines suggest that two counterclockwise vortices at points G3 and G4 add to the vortices at points G1 and G2. The impeller exit (diffuser inlet) circle acts as it were the wall of a solid body. The measured flow pattern near the impeller exit coincides with another experimental result[19] which shows that the fluctuation of $\nu_r$ is smaller than that of $\nu_\theta$.

5.3 Rotational speed of cells

Jansen has developed a theory about rotating stall
and has represented the rotational speed of cells $f_r$ [s$^{-1}$] in a non-dimensional form given by equation (1) as a function of the inlet flow angle $\tilde{\alpha}$:

$$\Omega = 2\pi r_s^2 f_r / r_s v_e$$  \hspace{1cm} (1)

In the theory, the rotating stall is maintained when $\tilde{\alpha} = 0$ but the flow in the diffuser is stable (no rotating stall) when $\tilde{\alpha} > 0$. The measured rotational speed, however, is usually compared with the theoretical value in the case of $\tilde{\alpha} > 0$ because a rotating stall actually occurs when $\tilde{\alpha} > 0$. The measured values of $\Omega$ in the authors' previous experiments$^{(2)(6)}$ are larger than the theoretical values, but the definition by Eq. (1) is useful since the measured values enter into a certain range of $\Omega$.

### 5.3.1 Measured values

Figure 9 shows the variation of $f_r$ with $\tan \tilde{\alpha}$. Here, $\tan \tilde{\alpha}$ is defined as the ratio of time-averaged radial velocity $\bar{v}_r$ to the tangential one $\bar{v}_e$ measured at $r/r_s = 1.05$ for each diffuser. No systematic variation of $f_r$ with $b$ is observed. In the comparison of $f_r$'s for $b = 17.8$ mm with those for $b = 9.1$ and 7.1, the $f_r$'s for the latter group are smaller in the range $\tan \tilde{\alpha} = 0.07 \sim 0.19$. This tendency becomes obvious in Fig. 10.

$\Omega$'s for $b = 17.8$ are almost constant regardless of $\tan \tilde{\alpha}$. On the other hand, $\Omega$'s for $b = 27.1, 9.1$ and 7.1 decrease gradually with increasing $\tan \tilde{\alpha}$ (Fig. 10). This difference between the two groups is not caused by the difference in the cell number.

The trend of Jansen's $\Omega$ is similar to that of the group $b = 27.1$ etc., but the theoretical values are generally smaller than the measured values. The prediction of $f_r$ based on Jansen's theory may result in a large error.

The experimental equations of $\Omega$ are obtained as Eqs. (2) and (3) from the present data. For two groups, $b = 17.8$ and $b = 27.1$ etc., the method of least squares was used. Here, $\tilde{\alpha}$ is considered to be equal to $\tilde{\alpha}$.

$$\Omega_1 = 1.21$$  \hspace{1cm} (2)

$$\Omega_2 = 1.16 - 1.71 \tan \tilde{\alpha}$$  \hspace{1cm} (3)

As shown in this experiment, several $\Omega$'s are realizable for the same $\tan \tilde{\alpha}$, but under the present conditions, there is no method by which a single $\Omega$ can be determined. In the previous experiments by the authors$^{(2)(6)}$, $\Omega_1$ appeared as shown in Fig. 11.
5.3.2 Prediction of rotational speed

The rotational speed of cells \( f_i \) can be predicted using Eqs. (2) and (3). However, the tangential velocity \( \bar{v}_n \) at the diffuser inlet under the rotating stall condition should be known. It is convenient to apply the slip coefficient of the impeller.

The slip coefficient is defined as \( K = \bar{v}_n / \bar{v}_{n\text{,in}} \), here, \( \bar{v}_{n\text{,in}} \) = tangential velocity of the flow at the impeller exit, \( \bar{v}_n \) = tangential velocity for an infinite number of blades. The values of \( K \) based on measured \( \bar{v}_n \) are as follows: \( K = 0.74 \) at the impeller design point \( \bar{a}_r = 0.152 \) for \( b = 17.8 \), and \( K = 0.67 \) at the best efficiency point \( \bar{a}_r = 0.167 \) for the impeller of Ref. (6). These correspond to 90% and 83%, respectively, of Wiesner’s \( K^{(11)} \). Wiesner’s equation can not give a perfectly accurate value of \( \bar{v}_n \) even for a steady flow, but the above values of \( K \) may show the drop of the impeller performance due to the rotating stall of the diffuser.

The tangential velocity \( \bar{v}_n \) under the rotating stall condition is calculated from \( \bar{v}_n = 0.87 \times \bar{v}_{n\text{,in}} \), where \( \bar{v}_{n\text{,in}} \) is calculated by Wiesner’s equation. The predicted values of \( f_i \) by this method are shown in Table 1 for some diffusers. In the case of diffusers (1) \( \sim \) (3), the values are at the impeller design point or at the best efficiency point, and (4) at the ignition point of the rotating stall. The value of \( f_i \) at \( Q = 0 \) can be predicted using Stepanoff’s \( K \). Stepanoff gives \( K = 0.725 \) at \( Q = 0 \) for impellers of all specific speeds and for all blade exit angles \(^{(11)} \). The predicted values of \( f_i \) by the same method are shown in Table 2.

The \( f_i \)'s can be predicted with accuracy by this method as shown in Tables 1 and 2. The \( f_i \)'s at flow rates are given by a reasonable interpolation method using \( f_i \)'s at the impeller design point, the ignition point and zero flow rate.

| DIFFUSER | \( f_i \) | \( f_i \) | \( f_i \) |
|----------|----------|----------|
| (1) \( b = 17.8 \) | 1.525 | 4.5 | 3.4 | 4.6 | 3.8 |
| (2) Ref. (2) | 0.248 | 5.6 | 3.4 | 5.9 | - |
| (3) Ref. (6) | 0.167 | 5.5 | 3.9 | 5.4 | - |
| (4) Ref. (9) | 0.097 | 29.1 | 23.2 | 25.6 | - |
| (5) 0.059 | 29.8 | 26.1 | - | 24.5 | |

Table 1 Predicted and measured values of rotational speed of cells \( f_i \) and \( f_i \)'s are obtained from Eqs. (2) and (3) respectively, * a value for \( b = 9.1 \).

| DIFFUSER | \( f_i \) | \( f_i \) |
|----------|----------|
| (1) \( b = 17.8 \) | 5.1 | 5.2 |
| (2) Ref. (2) | 7.0 | 6.8 |
| (3) Ref. (6) | 6.4 | 6.7 |

Table 2 Predicted and measured values of rotational speed of cells at \( Q = 0 \).

5.4 Critical inlet flow angle for onset of a rotating stall

When the inlet flow angle \( \bar{a}_r \) becomes smaller than a certain value, the flow on the diffuser wall becomes an inward (reverse) flow at a certain radius. Senoo and Kinoshita have calculated the critical inlet flow angle \( \bar{a}_r \) for the onset of reverse flow using the method of Ref. (7) and they have described the relation, from experimental results, between \( \bar{a}_n \) and the critical inlet flow angle \( \bar{a}_n \) for the onset of a rotating stall, as \( \bar{a}_n = 0.88 \times \bar{a}_r \). The variation of \( \bar{a}_n \) with the non-dimensional width of the diffuser \( \sqrt{r_i} \) has been shown in the figure of Ref. (9). The predicted \( \bar{a}_n \)'s have been examined in the range \( r_i / r = 0.015 \sim 0.13 \) but not beyond 0.13, so the applicability of their prediction method has not yet been proved for a wide diffuser beyond \( r_i / r = 0.13 \).

5.4.1 Measured values

The inlet flow angles just before a rotating stall are obtained by the experiment in which the suction valve is throttled gradually for four diffusers (\( r_i / r = 2.35 \)) including the diffuser beyond \( r_i / r = 0.13 \). The critical inlet flow angles \( \bar{a}_n \)'s are obtained from the above angles (see 4.3). Figure 12 shows the relation between \( r_i / r \) and \( \bar{a}_n \). The open circles are the present results and the broken line is Senoo-Kinoshita's prediction curve calculated again by the authors. The present \( \bar{a}_n \)'s, except for \( r_i / r = 0.317 \), are considerably smaller than the predicted values. The values previously measured by the authors\(^{(20)}\) are also smaller than the predicted values.

What change occurs, corresponding to this, in the
reverse flow layer on the diffuser wall? The prediction curve is based on the critical inlet flow angle (for the onset of reverse flow) which is calculated on the assumption that the velocity distribution of the main flow is uniform and the boundary layers are very thin at the diffuser inlet. Reference (8) shows that the maximum thickness of the reverse flow layer becomes 3.5% that of the diffuser width when the inlet flow angle becomes $\theta_0$.

5.4.2 Relation with reverse flow layer

Figure 13 shows the radial velocity distribution along the diffuser width just before a rotating stall in the case of $b/r_1=0.208$. The circles and the full lines show measured and calculated values, respectively. The calculation was carried out by the method of Ref. (7) using a measured velocity distribution as an initial value. The calculation method is useful since calculated values agree well with measured values.

Reverse flow layers appear on both walls ($z/b=0.1$). The variations in the reverse flow layer thicknesses with the radius ratio are shown in Fig. 14(a). The calculated maximum thickness of the reverse flow layer is about 10% that of the diffuser width at $z/b=0$ and about 13% that at $z/b=1$. In the case of $b/r_1=0.317$, $\delta_R$ is close to Senoo-Kinoshiba’s predicted value but the calculated maximum thickness is about 9% that of the diffuser width as shown in Fig. 14(b).

In many cases, the velocity distributions at the diffuser inlet are nonsymmetric with respect to the center line of the diffuser width, hence the values of the reverse flow layer thickness are different between both walls at an arbitrary radius. The equivalent symmetric velocity distributions are supposed to estimate real nonsymmetric reverse flow layers. The equivalent initial velocity distribution at $r/r_1=1.31$ is obtained from the measured value as follows: in the case where the boundary layers are fully developed along the diffuser width, the maximum velocity is given by the measured maximum velocity and the angle $\varepsilon$ between the maximum velocity vector and the wall streamline is given by averaging the measured values on both walls. In the case where a main flow exists, the velocity of the main flow is given by averaging the maximum and minimum velocities of the real main flow, and the boundary layer thickness and $\varepsilon$ are given by averaging the measured values on both walls.

The calculated values of the maximum thickness $S$ of the reverse flow layers are listed in Table 3 as the percentage of $S/b$. When $b/r_1$ decreases, $S/b$ increases. Present values of $S/b$, except for $b/r_1=0.317$, are larger than Senoo-Kinoshiba’s value (3.5%).

The calculations were further carried out assum-
Table 3  Calculated maximum thickness of supposed reverse flow layer (just before rotating stall), values in parentheses are for $\varepsilon=5.7^\circ$

<table>
<thead>
<tr>
<th>$b/r_1$</th>
<th>$\alpha_0$</th>
<th>Initial Condition at $r/r_1 = 1.31$</th>
<th>$\varepsilon^*$</th>
<th>$S/b \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.317</td>
<td>16.2</td>
<td>MAIN FLOW-BOUNDARY LAYERS</td>
<td>13.2</td>
<td>2.3 (1.7)</td>
</tr>
<tr>
<td>0.230</td>
<td>11.7</td>
<td>FULLY DEVELOPED BOUNDARY LAYERS</td>
<td>24.2</td>
<td>7.1 (6.2)</td>
</tr>
<tr>
<td>0.106</td>
<td>7.7</td>
<td></td>
<td>23.0</td>
<td>9.2 (7.4)</td>
</tr>
<tr>
<td>0.083</td>
<td>6.9</td>
<td></td>
<td>23.0</td>
<td>10.6 (7.0)</td>
</tr>
</tbody>
</table>

In this table, $\varepsilon$ was small (5.7 deg) and $\alpha_0$ was unchanged. As shown in parentheses in Table 3, $S/b$ decreases slightly. If one assumes that a rotating stall occurs when $S/b$ becomes larger than a certain value, the values (2.5~10.8) in Table 3 give the criteria for the onset of a rotating stall for each $b/r_1$.

The values of $S/b$ for $\varepsilon=5.7$ deg suggest that the rotating stall begins at a smaller $\alpha_0$ than the present value when $\varepsilon$ is smaller than the present measured value listed in Table 3. The deviation of $\alpha_0$, however, is small that $\varepsilon$ is not greatly different from the present measured value.

5.4.3 Predicting equation

It is reasonable to use $S/b$ as the criteria to predict the onset of a rotating stall, but the flow condition should be determined through calculation. It is convenient that $\alpha_0$ is represented in the equation as a function of $b/r_1$, and that the rotating stall can also be predicted when the velocity distribution at the diffuser inlet is not known. However, some prediction errors caused by differences in the velocity distributions will appear, hence an adequate margin should be allowed to avoid a rotating stall.

Equation (4) is given by the method of least squares using the present result and data in the literature\(^{(21)(6)(b)}\):

$$\alpha_0 \ [\text{deg}] = 28.49 \sqrt{b/r_1} \quad (4)$$

The predicting equation is obtained as Eq. (5) by allowing a margin of 2 deg, considering the scatter of the data in Fig. 12.

$$\alpha_0 = 28.49 \sqrt{b/r_1} + 2 \quad (5)$$

Equation (5) is useful only for the purpose of avoiding a rotating stall, but it does not assure the onset of a rotating stall at the calculated $\alpha_0$.

5.4.4 Effect of diffuser radius ratio

When the radius ratio of the diffuser with $b/r_1 = 0.208$ is decreased from $r_0/r_1 = 2.35$ to 2.0, the measured $\alpha_0$ is decreased from 11.3 to 9.7 deg and the periodicity of the pressure wave form at the initiation point is weakened. As shown in Fig. 12, the reverse flow layer is not measured near the diffuser exit ($r/r_1 = 2.30$) for the diffuser with $r_0/r_1 = 2.35$. However, the reverse flow layer appears, as shown in Fig. 14(a) at the exit for $r_0/r_1 = 2.0$. It is supposed, from this, that the rotating stall is repressed when a reverse flow layer appears at the diffuser exit. With respect to the authors' data shown in Fig. 12, the measured pressure fluctuations at the initiation point are periodic, hence the reverse flow layers will not reach the exit.

The dependency of $\alpha_0$ on the radius ratio is obvious, hence the application range of Eq. (5) should be taken as $r_0/r_1 \leq 2.7$, from the experimental conditions for the data used here, and simultaneously, the value given by Eq. (5) should be regarded as the upper limit of the critical inlet flow angle.

6. Conclusions

The main results in this paper are as follows:

1. A local velocity fluctuation was found at the reverse flow layer just before the rotating stall and the flow condition in the diffuser for that fluctuation was made clear. The reverse flow layer causes the rotating stall of the diffuser.

2. The characteristics of a fully developed rotating stall were made clear.

3. Experimental equations for the non-dimensional rotational speed of cells were presented (Eqs. (2) and (3)) and a method of predicting the rotational speed using these equations was proposed. The values predicted by this method agreed well with measured values.

4. The equation for predicting the critical inlet flow angle for the onset of a rotating stall was presented for the diffuser with no scroll (Eq. (5)). The application range is $b/r_1 = 0.01 \sim 0.32$ and $r_0/r_1 \leq 2.7$.

5. Some new information on the reverse flow layer just before a rotating stall was obtained from the experiment and the numerical analysis.

(a) $S/b$ becomes larger for smaller $b/r_1$.

(b) When $S/b$ is taken as a criterion for the onset of a rotating stall, $\alpha_0$ becomes smaller for smaller $\varepsilon$.

(c) When $r_0/r_1$ is made small and a reverse flow layer appears at the diffuser exit, $\alpha_0$ becomes small.

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References


(2) Imai, K. and Tsurusaki, H., Proc. ASME Winter Annual Meeting, Flow in Primary, Non-


