

## Behavior of Swirling Flow Generated by Annular Guide Vanes

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### Abstract

Annular inlet guide vanes are installed in various turbomachines and have an expected effect on the flow rate and inlet pressure control. They are also known to reduce the pressure loss at rotor blade collisions and to expand the operating range. Annular inlet guide vanes are often used as a means of generating swirling jet flows. However, it has been reported that flow instabilities that accompany vibration as well as noise downstream of annular guide vanes both occur when the vane angle is small. The relationship between flow instability and jet flow characteristics remains unclear. In this study, we attempt to clarify the effect of flow instability downstream of guide vanes on the behavior of a swirling jet. The angular momentum was controlled by adjusting the angle of the annular guide vanes under constant flow rate conditions. A flow visualization using a smoke generator was then executed, and numerical calculations were performed. A typical result showed that the direction of the swirling jet flows depends on the flow characteristics downstream of the annular guide vanes.

**Keywords:** annular guide vanes, swirl flow, angular momentum, swirl number, centrifugal force, flow instabilities

### 1 Introduction

Many researchers, primarily in the field of combustion, have studied the dynamic characteristics of a swirling flow, which is closely related to the behavior of a flame inside an engine [1]. It is known that the flow field of a swirling flow greatly depends on the angular momentum (strictly, the swirl number) [2][3]. For a swirling flow that is opened to semi-infinite space, the flow when the swirl number is low and when the angular momentum is relatively small forms a jet flow structure with the swirl. By contrast, a jet flow is known not to occur when the swirl number is large and when the flow that spreads in a radial direction is formed by a centrifugal force.

Annular guide vanes are sometimes used as a means of generating a swirling flow. Annular inlet guide vanes are installed in various turbomachines and have an expected effect on the flow rate control. They are also known to reduce collision pressure loss at the blade and expand the working range. However, it has been reported that flow instabilities that accompany vibration as well as noise downstream of annular guide vanes both occur when the vane angle is small [4]–[7]. It is believed that the aforementioned unsteady flow motion is essentially two-dimensional, and oscillation occurs because the disturbance expressed by the cell structure propagates in a circumferential direction. Because this phenomenon is related to the lifetime and performance degradation of fluid machines, many studies on the onset conditions and occurrence mechanisms of flow instabilities have been conducted.

However, insufficient knowledge exists regarding the characteristics of swirling flows in terms of the instability of the cell structure generated downstream of annular guide vanes. In particular, many uncertainties remain regarding the phenomenon of an unsteady whirling jet.

In this study, we attempted to elucidate the influence of flow instability downstream of the guide vanes on the behavior of swirl flows released into the atmosphere. The angular momentum was controlled by adjusting the angle of the annular guide vanes under constant flow rate conditions. Flow visualizations and numerical simulations were conducted.

## 2 Experimental and Numerical Methods

Figure 1 shows a schematic of the experimental setup. The working fluid was air, and a ring blower (Fuji Electric Motor VFC408P) was used to generate the flow. When the fluid passed between two disks (outside radius  $r_0 = 160$  mm), circumferential velocity components were given by 36 variable guide vanes. For the sake of simplicity, a flat blade (blade span  $s = 10$  mm, chord length  $C = 30$  mm, blade thickness  $t = 1$  mm) was used for the guide vanes. Considering the thickness of the disk,  $L$  was set to 15 mm.

Figure 2 shows the coordinate system. In this study, we report experimental results under the conditions of radius ratios of  $r_2/r_3 = 1.1$  and  $2.5$ , where the guide blade exit radius  $r_2$  and device exit radius  $r_3 = 50$  mm. A float-type flowmeter was used for flow measurements. The flow rate in this study was constant at  $Q = 0.01$  m<sup>3</sup>/s. In the flow visualization experiment, tracer particles were generated using a smoke generator (Dainichi Industrial Co., Ltd. Porta Smoke) visualized with a green laser sheet (Kato Koken Co., Ltd.) and captured with a digital camera (Casio EX-100Pro).

SC/Tetra (Software Cradle Co., Ltd.) was utilized as software for the 3D numerical simulations. Boundary conditions and typical meshes for calculations are shown in Figures 3 and 4(a)–(b), respectively. The flow rate specification of the inlet was  $Q = 0.01$  Pa, the surface pressure specification of the outlet was  $P = 0$  Pa, and the walls were stationary.

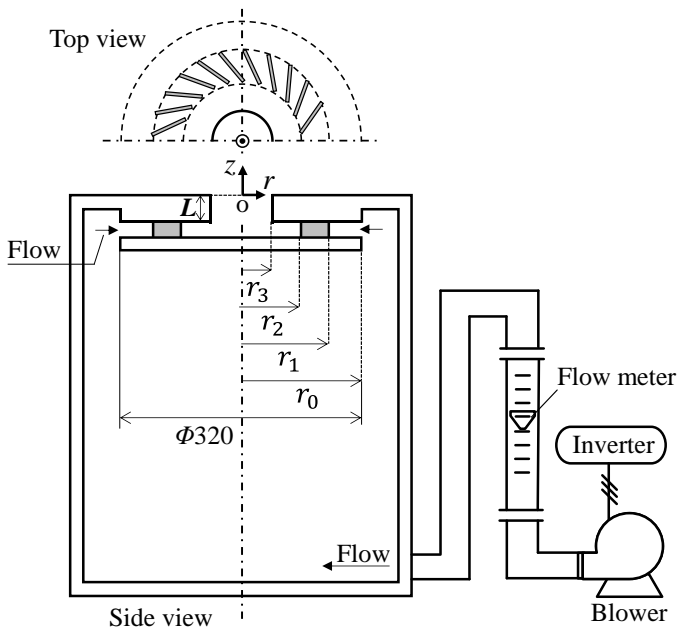


Fig. 1 Schematic

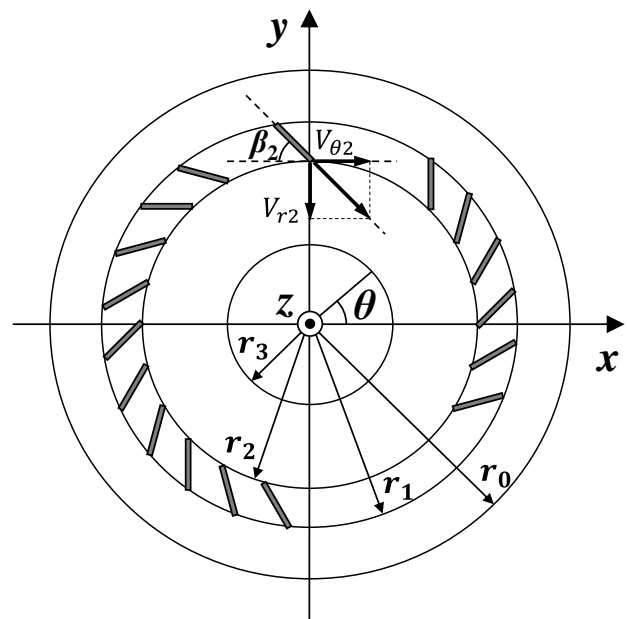


Fig. 2 Coordinate system

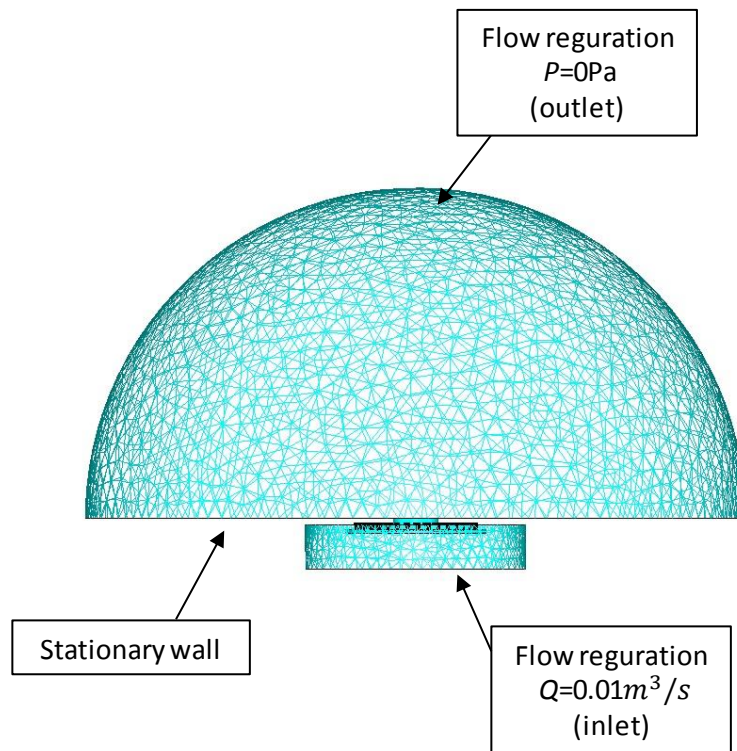


Fig. 3 Boundary conditions of the numerical calculation

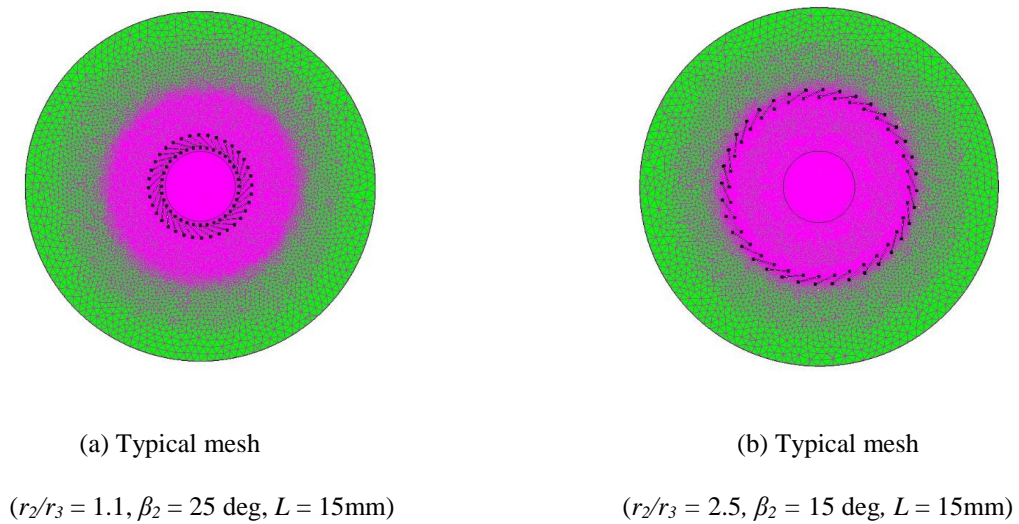


Fig. 4 Typical meshes for numerical calculations

### 3 Results and Discussion

Figure 5 shows the instantaneous pressure distribution in the x-y plane at the midspan of the annular guide vanes obtained by numerical calculations. Figure 5(a) and (b) show the results of numerical calculations, where (a) used an inner and outer diameter ratio of  $r_2/r_3 = 1.1$  and  $r_3/r_2 = 0.9$ , respectively, with the trailing edge of the blade angle  $\beta_2$  at 25 deg, and (b) used an inner and outer diameter ratio of  $r_2/r_3 = 2.5$  and  $r_3/r_2 = 0.4$ , respectively, with the trailing edge of the blade angle  $\beta_2$  at 25 deg. Assuming that Kutta's condition was satisfied at the blade outlet, the theoretical circumferential velocity at the device outlet was (a)  $u\theta = 6.8262$  m/s, and (b)  $u\theta = 11.8794$  m/s. In other words, the circumferential velocity of (b) was higher than the circumferential velocity of (a), and the angular momentum of (b) was greater than that of (a). The disturbance could be seen in both situations, where the number of cells in (a) was  $m = 4$  and the number of cells in (b) was  $m = 1$  simultaneously. This disturbance was confirmed to propagate in the circumferential direction. The pressure oscillation amplitudes at the outlet of the two devices were compared, and it was obvious that the value of (a) was overwhelmingly smaller than that of (b).

Figures 6 and 7 show examples of the behavior of swirling jets.

Figure 6 shows the results for  $r_2/r_3 = 1.1$  ( $r_3/r_2 = 0.9$ ) and  $\beta_2 = 25$  deg, and Figure 7 shows the results for  $r_2/r_3 = 2.5$  ( $r_3/r_2 = 0.4$ ) and  $\beta_2 = 15$  deg. Here, (a) is a time-averaged velocity vector diagram on the meridian plane obtained by calculation, and (b) is a photograph captured in a visualization experiment. Figures 6 and 7 show that the numerical calculation results shown in (a) and the experimental results shown in (b) were in qualitative agreement. In other words, in both the numerical calculation and experiment, the annular flow accompanied by swirling spread in the radial direction (horizontal direction in Figure 6 and 7) by the centrifugal force shown in Figure 6. Figures 6 and 7 reveal that, although the estimated angular momentum was large, an advancing jet flow was formed in the axial direction (strictly, as shown in Figures 6 and 7).

The main reason the jets differ in direction is the presence of flow instability downstream of the annular guide vanes. Accordingly, it can be inferred that the flow characteristics of the swirling flow released to the atmosphere depend not only on the angular momentum but also on the vibration characteristics.

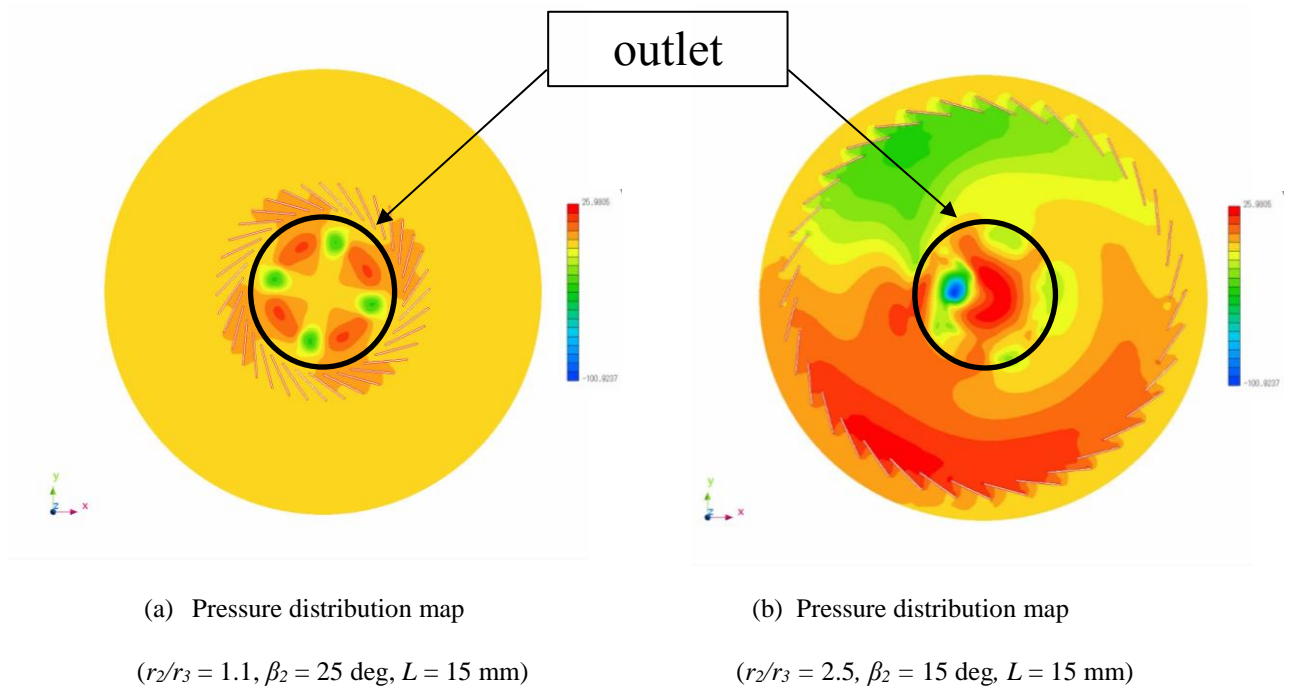
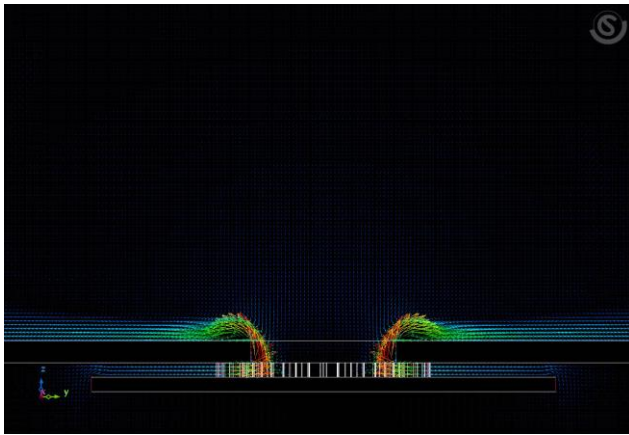
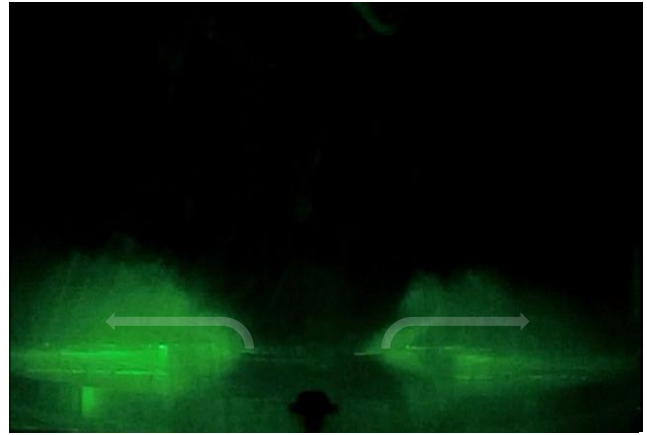


Fig. 5 Pressure distributions for numerical calculations



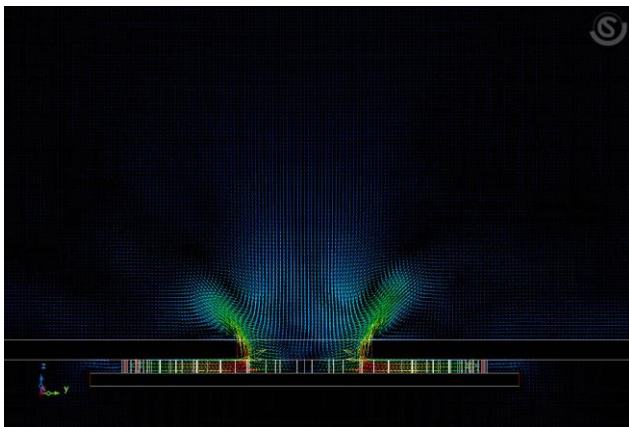
(a) Velocity vector map



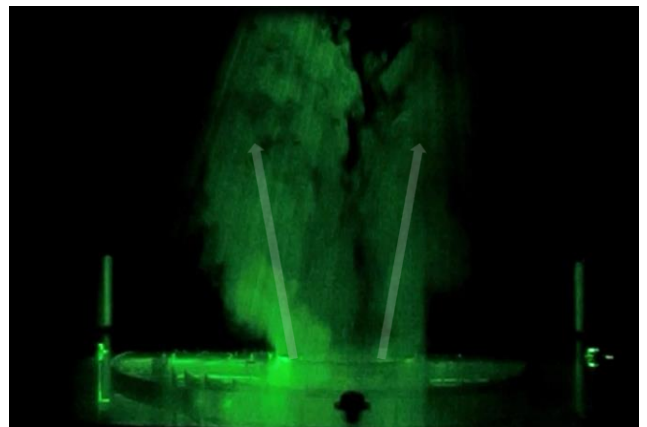
(b) Visualization map

Fig. 6 Behavior of swirling flows on numerical analysis and experimental results

$$(r_2/r_3 = 1.1, \beta_2 = 25 \text{ deg}, L = 15\text{mm})$$



(a) Velocity vector map



(b) Visualization map

Fig. 7 Behavior of swirling flows on numerical analysis and experimental results

$$(r_2/r_3 = 2.5, \beta_2 = 15 \text{ deg}, L = 15\text{mm})$$

#### 4 Conclusion

In this study, we attempted to clarify experimentally the effects of flow instability downstream of guide vanes on swirling flow behavior. In general, it is known that the behavior of swirling flows with the same flow rate (momentum) depends on the angular momentum. However, the results showed that the behavior of swirling flows with the same flow rate (momentum) not only depends on angular momentum, but on the flow instability with the cell structure downstream of the annular guide vanes as well as on vibration characteristics.

Thus, it was shown that the behavior of a swirling jet generated by annular guide vanes depends on the angular momentum and the characteristics of oscillating flow downstream of the vanes.

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