PERFORMANCES OF CASCADE OF BLADES WITH SMALL ASPECT RATIO

PART 1. PERFORMANCES AT THE CENTER OF BLADE SPAN*

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Abstract

Performances of the compressor type cascade of blades with small aspect ratio were experimentally obtained at the center of blade span. The blade profile dimensions were 50 mm in span, and 24, 36, 48 and 60 mm in chord length which were 2.08, 1.39, 1.04 and 0.83 in AR (aspect ratio).

The results are as follows.

[1] In the case of α_i (attack angle) over about 5° ε (turning angle) increases and in the case $\alpha_i=0°$ it decreases gradually with increasing AR. These tendencies become clearer with increasing α (stagger angle).

[2] Total pressure loss coefficient takes a minimum value at $AR \fallingdotseq 1$ independently of α and α_i. (The Reynolds number effect has not been investigated in this report).

[3] (1) At α_i=constant, axial velocity ratio decreases gradually to a fixed value close to 1 with increasing AR in the case $\alpha=0°$.

(2) Axial velocity ratio keeps almost constant value independently of AR in the case $\alpha=30°$.

(3) In the cases $\alpha=50°$ and 60°, axial velocity ratio keeps almost constant value when AR is less than about 1, but when AR is larger it increases at $\alpha_i \geqq 5 \sim 10°$ and decreases at $\alpha_i=0°$ with increasing AR.

1. Introduction

In designing axial-flow compressor the blade span (or height) is decided by the predetermined flow rate and axial velocity, but because the blade chord length (or aspect ratio) can be selected freely, we must find the blade with most efficient chord length (or aspect ratio). In designing small-sized axial-flow compressor we often use blades with small chord length, but considering an effect of Reynolds number it may be desirable to use a blade with large chord length (which means small aspect ratio). But it seems that the research work on cascade of blades with small aspect ratio is not sufficient.

The experimental researches which examined systematically the effect of blade aspect ratio on cascade performances are ones, for example, by Miyaji[1] and Otsuka[2]. In the former report it was examined at almost constant Reynolds

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number that whether the cascade performance approaches to the two dimensional one by increasing the aspect ratio from 1 to 9, and in the latter it was found that the effect of the aspect ratio upon turning angle was considerable.

It seems that performances of the cascade of blades at the center of blade span, especially with small aspect ratio, are influenced by the secondary flow and by the growth of the boundary layers in the blade passage. But no reliable theory is available at present to predict these influences.

From reasons mentioned above, in which we considered the axial-flow compressor with definite blade height but indefinite chord length, authors thought that it was reasonable to do experiment on the cascade of blades with constant span and various kinds of chord length in the first step. Blade dimensions are 50 mm in span and 2.08, 1.39, 1.04 and 0.83 in aspect ratio. Accordingly Reynolds number based on blade chord length was varied with the change of aspect ratio. As aforesaid this plan of experiments may be a good simulation of the design condition of the axial-flow compressor in which the blade height is kept constant and the chord length is varied.

Of course, because a range of Reynolds number is alterd owng to the design conditions of the concerining axial-flow compressor, experiments over a wide range of Reynolds number are necessary to get universal data. This research work is the first step of a series of experiments, and the experiment to examine the effect of Reynolds number is now on the way.

Experiments were added to examine the effect of a pitch-chord ratio, and it was found that there was no substantial difference of the effect of aspect ratio upon cascade performances over the range of pitch-chord ratio 0.8~1.7.

2. Symbols

AR : aspect ratio, $AR = 2B/C$

a : blade pitch

$2B$: blade span

C : chord length

Δh : total pressure loss, $\Delta h_{mean} = p_{t1CL} - p_{t2mean}$

p : static pressurs

p_d : dynamic pressure, $p_{d2mean} = p_{t2mean} - p_2$

p_t : total pressure, $p_{t2mean} = \frac{1}{a}\int_0^a p_{t2}dt$

Re : Reynolds number, $Re = V_1C/\nu$

t : distance along traverse line in cascade direction

V : air speed, $V_1 = \sqrt{\frac{2}{\rho}(p_{t1CL} - p_1)}$, $V_2 = \sqrt{\frac{2}{\rho}(p_{t2mean} - p_2)}$

w_a : axial velocity, $\frac{w_{a2}}{w_{a1}} = \frac{V_2 \cos\gamma_{2mean}}{V_1 \cos\gamma_1}$

α : stagger angle

α_i : attack angle

γ : flow angle measured from axial direction, $\gamma_1 = \alpha + \alpha_i$, $\gamma_{2mean} = \frac{1}{a}\int_0^a \gamma_2 dt$

δ^* : displacement thickness of boundary layer before cascade

ε : turning angle, $\varepsilon = \gamma_1 - \gamma_{2mean}$

ζ : total pressure loss coefficient, $\zeta_2 = \Delta h_{\text{mean}}/p_{d\,2\,\text{mean}}$
ν : kinematic viscosity of air
ρ : air density

Subscript

1 : before cascade
2 : behind cascade (at traverse position)
CL : center of span

3. Apparatus and Procedure

The cascade wind tunnel used was a high-speed one which belongs to the laboratory of one of the authors. The schematic drawing is illustrated in Fig. 1. The blade profile is RAF-6 and its dimensions are 50 mm in span, and 24, 36, 48 and 60 mm in chord length. They are made of stainless steel. Profile data are

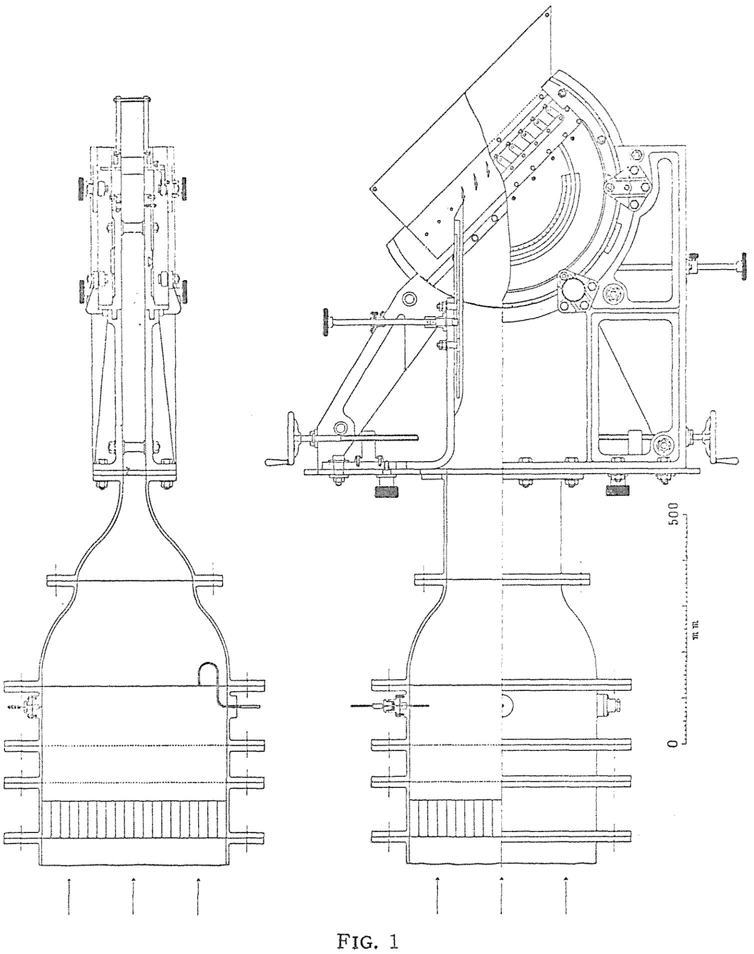
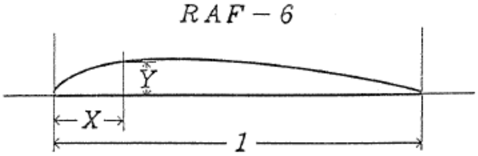


FIG. 1



X	Y
0.025	0.041
0.050	0.059
0.100	0.079
0.200	0.095
0.300	0.100
0.400	0.099
0.500	0.095
0.600	0.087
0.700	0.074
0.800	0.056
0.900	0.035
leading edge radius	0.010
trailing edge radius	0.0077

FIG. 2

illustrated in Fig. 2. Exit side walls are 70, 115 and 150 mm wide in axial direction and made of plastic[3]. Total pressure probe and yaw probe are made of cupronickel tube of 0.7 mm in diameter, and the latter is of arrow head type with the total pressure tube at the center of it. Static pressure probe is of 1 mm in diameter and of the same material.

Symbols concerning cascade arrangement are illustrated in Fig. 3.

Scopes of experiments are as follows. See 4–4 about cases in round brackets.

$$AR = 0.83,\ 1.04,\ 1.39,\ 2.08$$
$$a/C = (0.83),\ 1.04,\ (1.25),\ (1.67)$$
$$\alpha = 0°,\ 30°,\ 50°,\ 60°$$
$$\alpha_i = 0°,\ 5°,\ 10°,\ 15°$$

5~9 blades were used depending upon cascade configurations.

Measurements on the spanwise velocity distribution were done at 80 mm upstream of the support axis of blade to the axial direction. One typical example

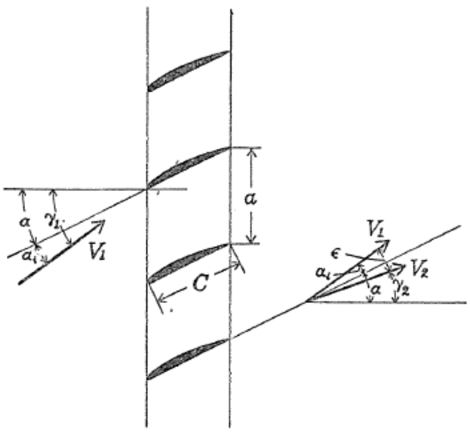


FIG. 3

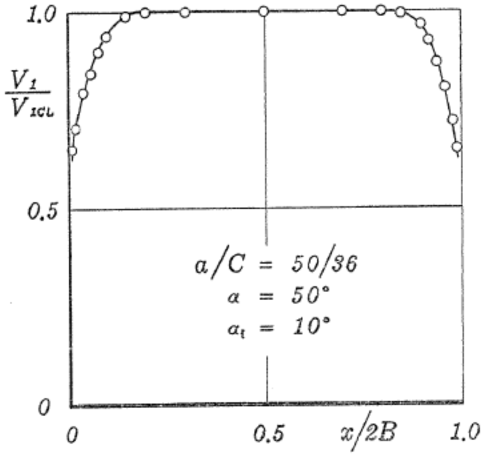


FIG. 4

TABLE 1.

a/C	AR	Re $\times 10^{-5}$	α	α_i	γ_1	δ^*/B (%)	a/C	AR	Re $\times 10^{-5}$	α	α_i	γ_1	δ^*/B (%)
1.04	0.83	2.7	0°	0°	0°	6.0	1.04	1.39	1.5	0°	0°	0°	5.8
				5	5	6.8					5	5	5.9
				10	10	6.3					10	10	6.1
				15	15	6.7					15	15	5.9
			30°	0	30	5.9				30°	0	30	5.8
				5	35	5.5					5	35	5.1
				10	40	5.2					10	40	5.4
				15	45	5.1					15	45	5.3
			50°	0	50	5.0				50°	0	50	5.1
				5	55	5.0					5	55	4.7
				10	60	4.6					10	60	4.0
				15	65	4.2					15	65	4.1
			60°	0	60	4.4				60°	0	60	4.2
				5	65	4.1					5	65	3.8
				10	70	4.0					10	70	3.8
	1.04	2.1	0°	0°	0°	5.3		2.08	1.0	0°	0°	0°	5.3
				5	5	5.3					5	5	5.1
				10	10	5.3					10	10	5.2
				15	15	5.2					15	15	5.1
			30°	0	30	4.9				30°	0	30	5.2
				5	35	5.3					5	35	5.0
				10	40	4.3					10	40	4.9
				15	45	4.1					15	45	4.7
			50°	0	50	3.9				50°	0	50	4.9
				5	55	3.9					5	55	4.6
				10	60	3.9					10	60	4.3
				15	65	4.0					15	65	4.2
			60°	0	60	3.7				60°	0	60	4.2
				5	65	3.5					5	65	3.7
				10	70	3.7					10	70	3.7
0.83	0.83	2.8	0°	10°	10°	6.2	0.83	1.39	1.6	0°	10°	10°	6.3
			60°	5	65	3.8				60°	5	65	3.7
				10	70	3.8					10	70	3.7
	1.04	2.2	0°	10°	10°	6.2		2.08	1.1	0°	10°	10°	5.3
			60°	5	65	4.0				60°	5	65	4.2
				10	70	4.3					10	70	5.9
1.25	0.83	2.7	60°	5°	65°	4.1	1.25	1.39	1.6	60°	5°	65°	4.5
				10	70	4.0					10	70	3.8
	1.04	2.1		5°	65°	4.0		2.08	1.1		5°	65°	3.9
				10	70	3.6					10	70	3.5
1.67	1.04	2.1	60°	5°	65°	4.2							
	1.39	1.6				3.9							
	2.08	1.1				4.1							

of the distribution is illustrated in Fig. 4. No qualitative difference is recognized in other cases. Displacement thickness of boundary layers before cascade are shown in Table 1. Dynamic pressure at the center section of cascade inlet was kept to 300 mmAq throughout the experiment, which means that inlet velocity was about 73 m/sec and Reynolds number was about $1.0 \sim 2.7 \times 10^5$ depending upon blade aspect ratio.

Exit flow traverses, ranging over about 2.4 pitches, were done on the exit flow angle and the total pressure at the midspan position distant 24 mm from the blade trailing edge[4].

4. Results and Considerations

Cascade performances at the center of span in the case $a/C=1.04$ are shown in sections from 4–1 to 4–3.

4–1. *Turning angle*

Fig. 5 illustrates the variation of turning angle with the inflow angle.

Fig. 6 shows the effect of aspect ratio on turning angle. At constant stagger angle, in cases of α_i over about 5° the turning angle increases and in case $\alpha_i=0°$ decreases gradually with increasing AR. These tendencies become clearer with increasing stagger angle. Particularly there are a few cases that the turning angle becomes negative at $AR=2.08$, and this is supposed to be caused by the condition that the boundary layer separation on the blade upper surface has tendencies to occur in the case of large stagger angle with increasing AR.

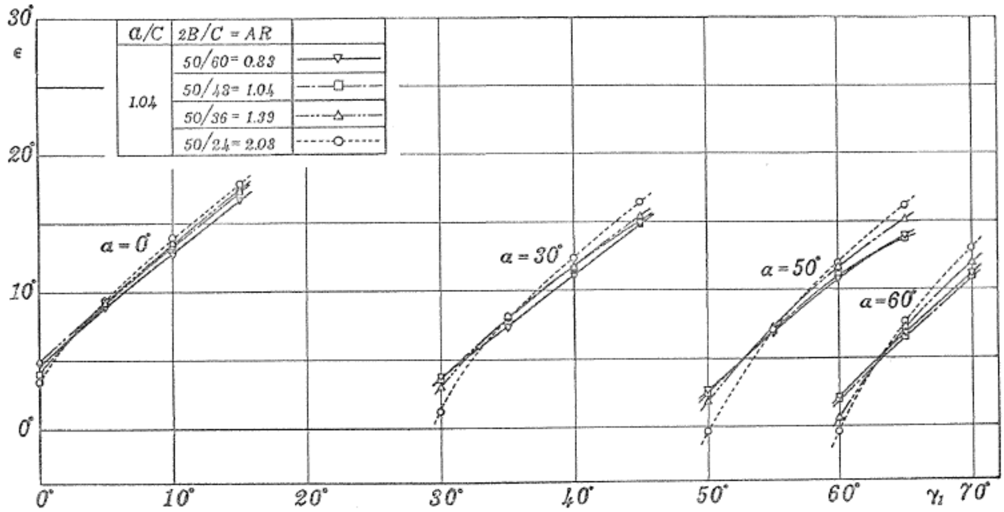


FIG. 5

4–2. *Total pressure loss coefficient*

Fig. 7 illustrates the variation of loss coefficient with the inflow angle. The loss coefficient ζ_2 takes a minimum value at about $\alpha_i=7\sim10°$ independently of α and AR.

Fig. 8 illustrates the effect of AR on the loss coefficient. It is noteworthy that ζ_2 takes a minimum value at $AR \fallingdotseq 1$ independently of α and α_i. ζ_2 increases when AR decreases less than about 1. This is supposed to be caused by the condition that boundary layers grown on side walls with increasing chord length are

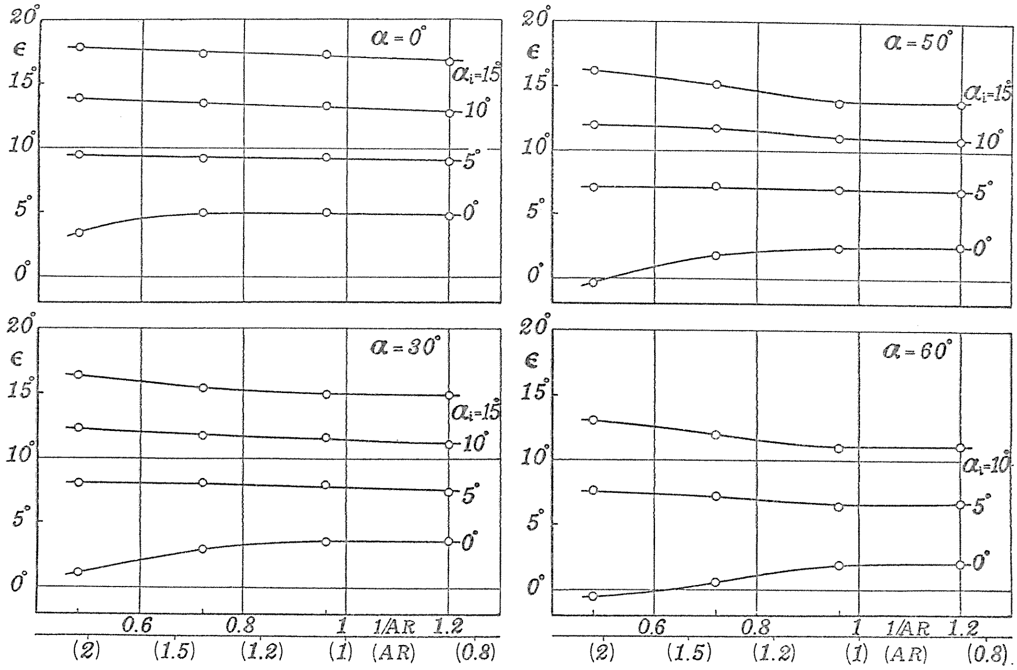

α = 0°
α = 50°
α = 30°
α = 60°
ε
αi=15°
10°
5°
0°
αi=10°
0.6
0.8
1
1/AR
1.2
(2)
(1.5)
(1.2)
(1)
(AR)
(0.8)

FIG. 6

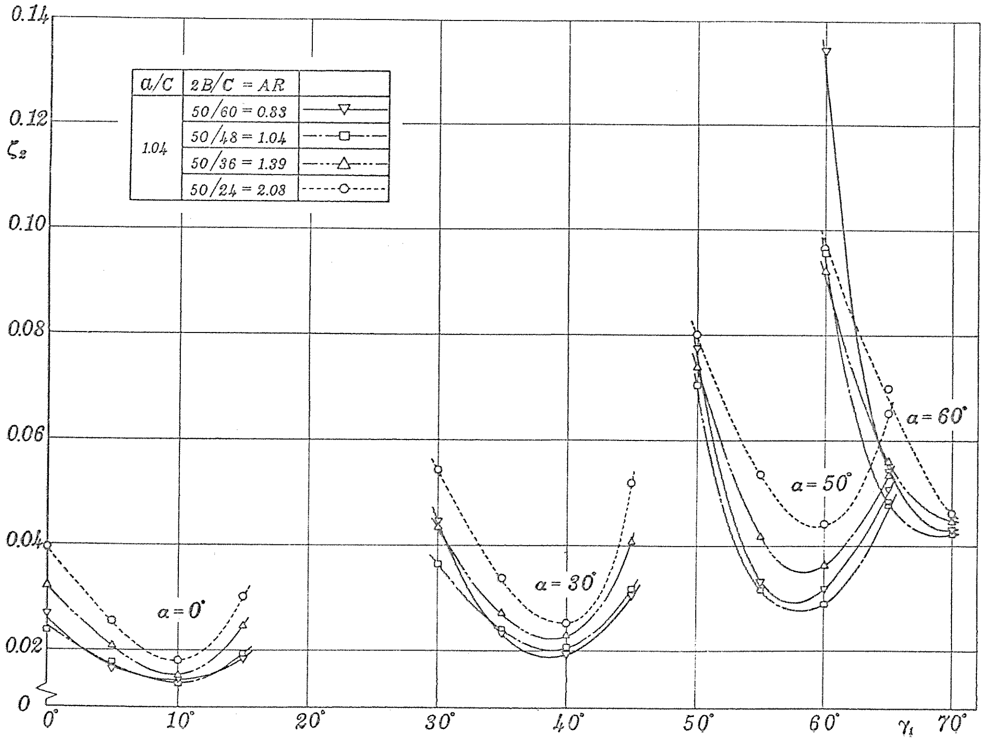

a/C
2B/C = AR
1.04
50/60 = 0.83
50/48 = 1.04
50/36 = 1.39
50/24 = 2.08
ζ2
α = 0°
α = 30°
α = 50°
α = 60°
γ1

FIG. 7

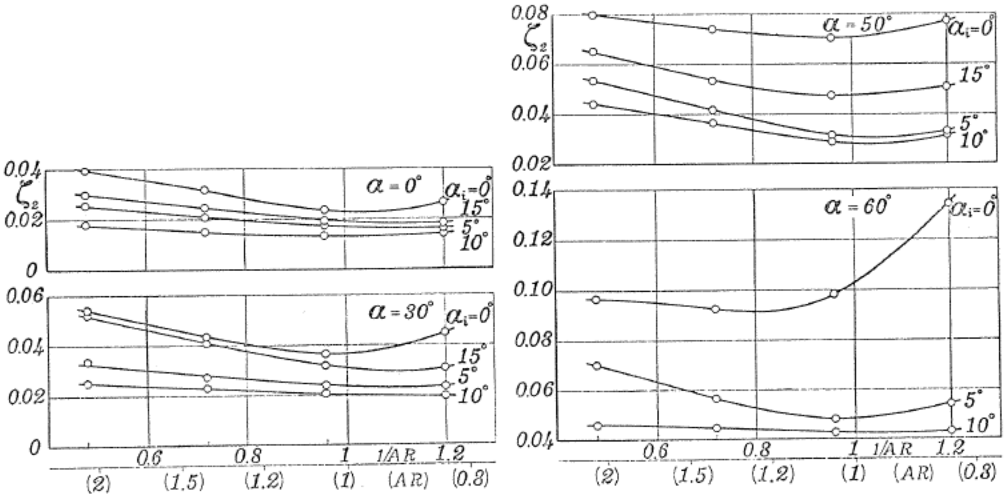


FIG. 8

blown together to the center of span, particularly on the blade upper surface, by the secondary flow. ζ_2 increases gradually when AR increases more than about 1.

From Miyaji's[1] and Otsuka's[2] reports it is supposed that the loss coefficient at the center of span (it is defined as $\Delta h_{mean}/p_{d1}$ in the former and $\Delta h_{mean}/p_{d2mean}$ in the latter.) approaches to the constant value which is peculiar to the cascade condition (blade profile, solidity, stagger angle and attack angle) with the increase of AR. It seems that the result of this research work does not correspond with the idea mentioned above, and this is probaly due to the fact that we did not perform the correction of Reynolds number effect to experimental results in this report. The experiment to examine the Reynolds number effect upon the performances of cascade of blades is now on the way.

Reynolds number correction to our results was done provisionally using the result of an experiment on a cascade of NACA 6409 blade profile[2]. The corrected result seemed to be roughly correspond with results of two reports mentioned above.

4–3. *Axial velocity ratio*

Fig. 9 illustrates the effect of the inflow angle on the axial velocity ratio. At constant aspect ratio $d(w_{a2}/w_{a1})/d\gamma_1$ becomes considerably larger with increasing stagger angle.

Fig. 10 illustrates the effect of aspect ratio. Aspect ratio effect is consideraly different depending on stagger angle.

(1) In the case $\alpha = 0°$ axial velocity ratio decreases gradually to a fixed value close to 1 with increasing AR.

(2) In the case $\alpha = 30°$ axial velocity ratio keeps almost constant value independently of AR at each α_i.

(3) In the cases $\alpha = 50°$ and 60°, axial velocity ratio keeps almost constant value in the region of $AR < 1$, and at about $AR > 1$ it increases in case of $\alpha_i \geqq 5 \sim 10°$ and decreases at $\alpha_i = 0°$ with increasing AR.

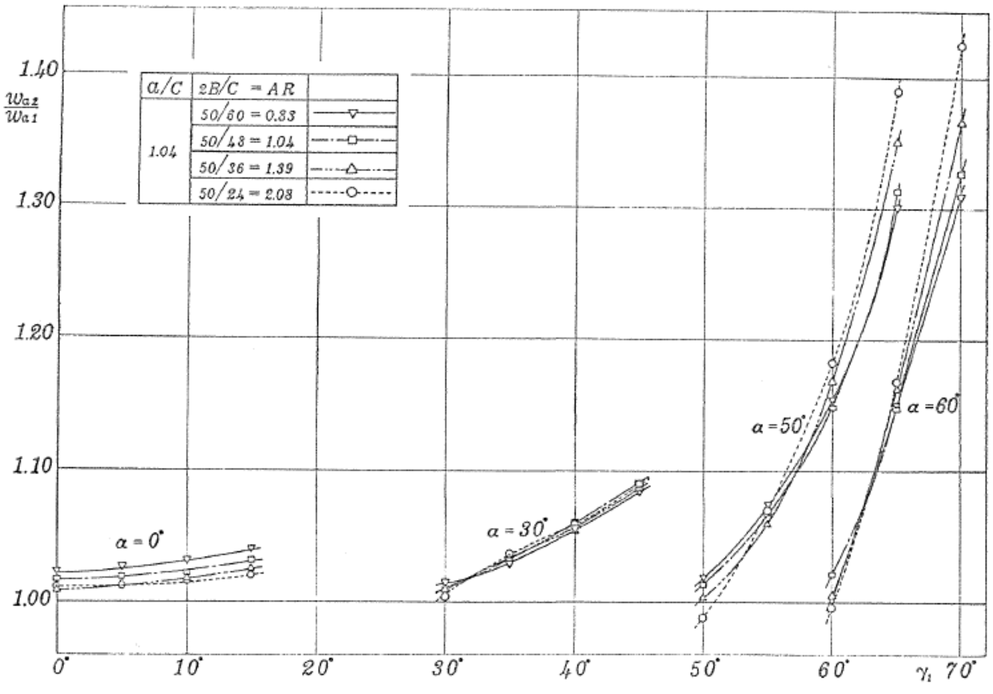


FIG. 9

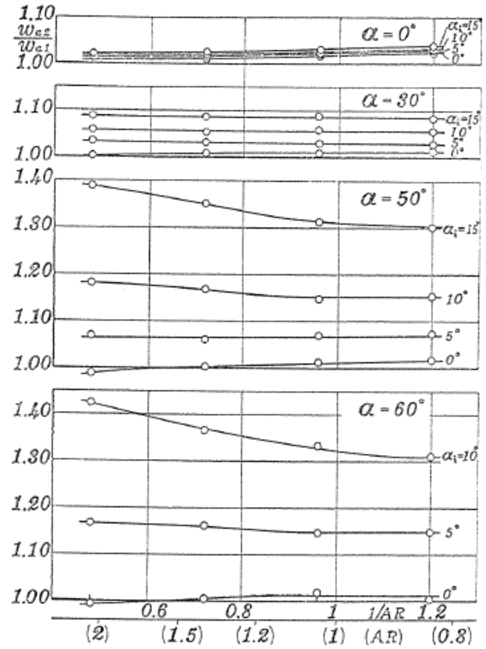


FIG. 10

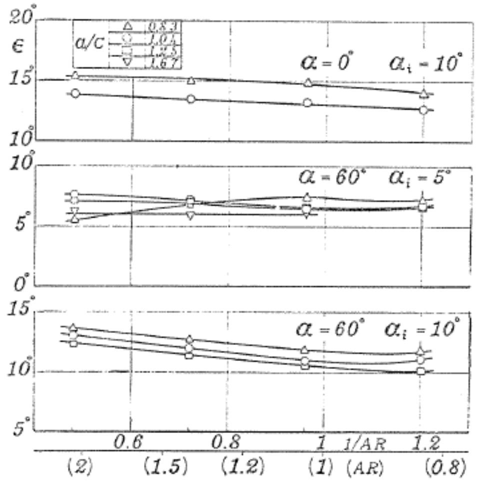


FIG. 11

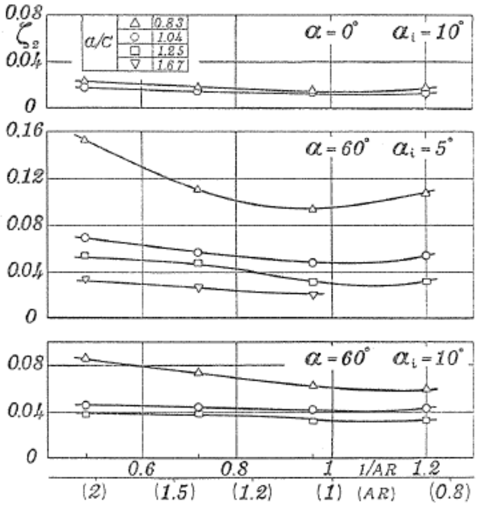


FIG. 12

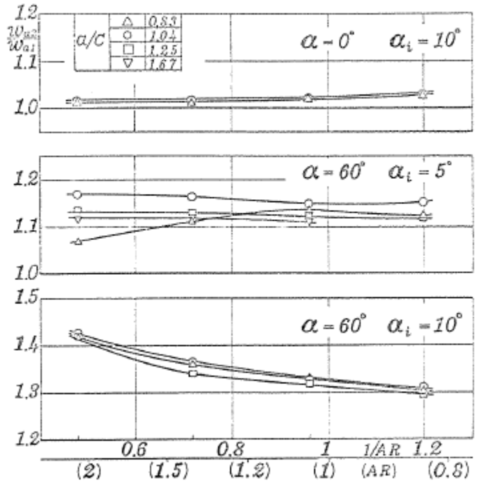


FIG. 13

The phenomenon mentioned in (3) that axial velocity ratio increases with increasing AR seems to be inconsistent with the idea generally supposed that the larger becomes the blade aspect ratio the less is the effect of the secondary flow upon cascade performances at the center of blade span.

4-4. Effect of pitch-chord ratio

Since results mentioned above were ones in the case $a/C=1.04$, experiments were performed changing $a/C=0.83\sim1.67$ to examine whether the effect of AR on cascade performances is different depending on a/C. The results are shown in Fig. 11, 12 and 13. It seems that there is no difference in the effect of AR on the turning angle and on the axial velocity ratio even if a/C is changed except the following. Only in the case $a/C=0.83$, $\alpha=60°$, $\alpha_i=5°$ the effect of a/C shows a little different tendency from others. Probably this indicates a variation of flow condition such as boundary layer separation on the blade surface. There is still the tendency that the loss coefficient takes a minimum value at $AR\fallingdotseq1$ independently of a/C.

5. Conclusions

Performances of the cascade of blades with small aspect ratio were obtained at the center section of the span.

(1) Turning angle

At constant α (stagger angle), in cases of α_i (attack angle) over about 5° ε (turning angle) increases and in the case $\alpha_i=0°$ decreases gradually with increasing AR. These tendencies become clearer with increasing α.

(2) Total pressure loss coefficient

It is noteworthy that ζ_2 (total pressure loss coefficient) takes a minimum value at $AR\fallingdotseq1$ independently of α and α_i. ζ_2 is subjected to the effect of Reynolds number which ranges approximately $1.0\sim2.7\times10^5$ in our experiment. As mentioned in **Introduction**, although Reynolds number correction was not made, our experimental condition seems to be one simulation of the design condition, but for obtaining universal results it is necessary to know the effect of Reynolds number. The experiment necessary to examine this effect is now on the way.

(3) Axial velocity ratio

The effect of AR on w_{a2}/w_{a1} (axial velocity ratio) varies with α. In the case $\alpha=0°$ w_{a2}/w_{a1} decreases gradually to a fixed value close to 1 with increasing aspect ratio. In the case $\alpha=30°$ w_{a2}/w_{a1} keeps almost constant value at each α_i independently of AR. In cases $\alpha=50°$ and $60°$ w_{a2}/w_{a1} keeps almost constant value when AR is less than about 1, but when AR is larger than about 1 w_{a2}/w_{a1} increases at $\alpha_i \geqq 5\sim10°$ and decreases at $\alpha_i=0°$ with increasing AR.

6. References

1) T. Miyaji: On the Effect of Blade Model Aspect Ratio in Cascade Experiments, Preprint of 672nd Meeting of Japan Society of Mechanical Engineers, Dec. 1959 (in Japanese).
2) S. Otsuka and K. Masuda: An Experiment about the Effect of Aspect Ratio on Cascade Performances, Transactions of the Japan Society for Aeronautical and Space Sciences, Vol. 9, No. 14, 1966.
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4) S. Otsuka and S. Hayashi: A Note about the Surveying Position of Outlet Flow in Cascade Experiments, Memoirs of the Faculty of Engineering, Nagoya University, Vol. 20, No. 2, 1968.