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ON THE CHARACTERISTICS OF THE TWO-DIMENSIONAL DIFFUSERS WITH SUCTION THROUGH PARALLEL POROUS SIDE WALLS

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Abstract

Measurements are performed on the velocity profiles and pressure recovery coefficient of diffusers of which inlet boundary layer is sucked out through porous plates consisting parallel walls of the diffuser. The pressure recovery coefficient measured indicates that the suction can improve the course of the pressure recovery even though it is applied on the parallel wall boundary layer of the diffuser. The pressure recovery process is classified into three kinds, the gradual type, the step type, and the step-gradual type. Flow patterns will be discussed in connection with the process.

1. Introduction

The boundary layer suction is one of the most important methods to controll the boundary layer behaviour and its application to the diffuser for improvement of the performance is a well established technique [1], [2]. Although rather large amount of investigations on the effects of suction were carried out [3]-[5], a number of factors affecting on the diffuser performance call for further studies about the problem. In the case of two-dimensional diffusers, the authors clarified the relationships among the shape of suction slits, the position of slits, volumetric suction ratio and the performance of the diffusers of which the boundary layer was removed through slits set on the diverging wall at the entrance section of the diffuser [6], [7]. The two-dimensionality of the diffuser geometry means merely that the diffusing region is bounded by two side walls parallel each other and two diverging walls.

In the course of above mentioned research on the diffuser performance, it was recognized that the suction through slits on the diverging wall sides sometimes lost the flow in the diffuser part its two-dimensionality and brought about decrease of the efficiency. Two-dimensional suction slits did not assure two-dimensional flow. It was considered that another method of suction should be investigated.

In this report, experimental results of the behaviour of the flow and the performance of the two-dimensional diffusers with suction through porous parallel side walls, not through diverging wall sides, will be presented. The diverging angle, the aspect ratio, the volumetric suction ratio of the diffuser were varied and their effects on the diffuser performance were examined.

Nomenclature (cf. Fig. 1)

x : streamwise coordinate of which origin is taken at the entrance section of the diffuser part.
y : transverse coordinate
z : spanwise coordinate pointing to the upward direction. x, y, z system makes a righthanded coordinate and the origin is located on the center of the duct.
2θ : diverging angle
b_0 : width of the inlet section
b : width of the pressure recovery duct
h : height of the duct
u : mean velocity
U_0 : velocity measured at the center of the inlet section
U : maximum velocity in the each measuring section
c_p : pressure recovery coefficient, Eq. (1)
c_{pi} : ideal pressure recovery coefficient, Eq. (2)
c_p' : reference pressure recovery coefficien, Eq. (4)
C_{p1}, C_{p2} : ratio of pressure recovery coefficient, Eq. (7)
δ^*, δ^{**} : usual displacement and momentum thickness respectively
q : suction flow rate
Q : volume flow rate of the diffuser
A : area of the passage
AR: area ratio of the outlet section to the inlet section
suffix 0 : $(*)_0$ represents the value of the reference section $x/b_0=-6.25$
suffix 1 : $(*)_1$ represents the value of the entrance section of the diffuser part

2. The Experimental Apparatus and the Definitions of Coefficients

Fig. 1 is a schematic presentation of the experimental apparatus. The tunnel is a suction type and has a rather long straight duct as a pressure recovery part. Aspect ratio of the inlet channnel is eight. The boundary layer is sucked out

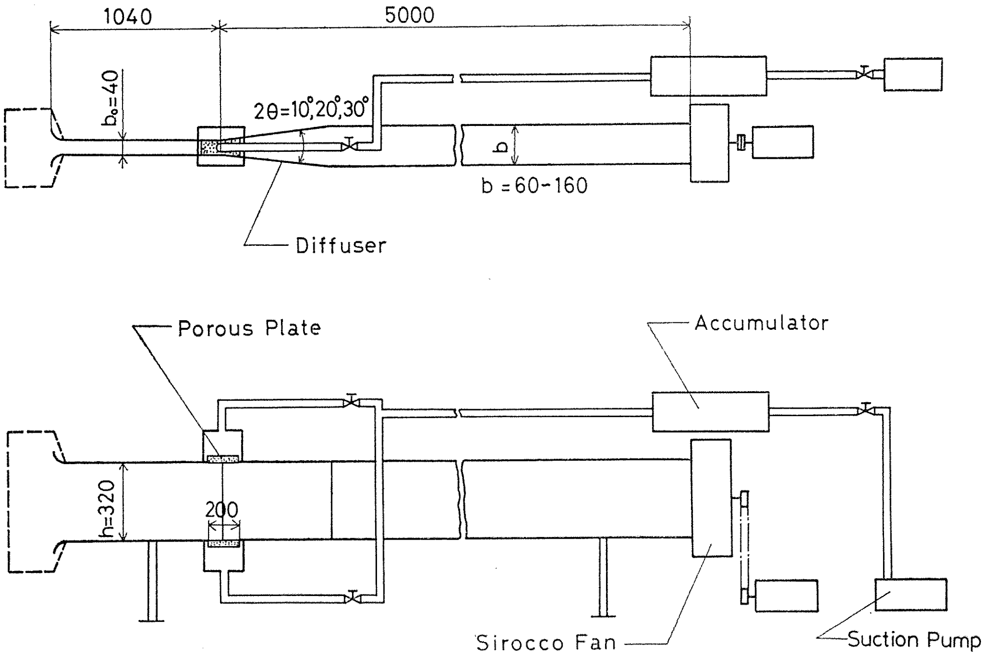

Fig. 1. Wind tunnel and suction system.

uniformly through porous plates forming parallel wall on the entrance section of the diffuser part as shown in Fig. 1. The suction flow rate through two porous plates is equally controlled by use of two valves. The volumetric flow rate of the main flow and of the suction were determined from the measured velocity profiles. Static pressure distributions were measured using fifty static pressure holes on the center line of the parallel wall side of the diffuser and of the pressure recovery duct. Flow visualization was made using tufts attached inside of the diffuser walls.

Diverging angle was varied $2\theta = 10°, 20°, 30°$. Area ratio of the outlet section to the entrance section of the diffuser was ranged $AR = 1.5, 2, 3, 4$. So the number of kinds of diffuser geometry was twelve and the volumetric suctio q/Q was changed 0.0, 0.039, 0.066, 0.107, 0.158 for each diffuser shape. Reynolds number was 6.2×10^4, which is based on inlet width. Velocity distributions were measured at the sections of $x/b_0 = -6.25$, 15, 25, 40.

The pressure recovery coefficient is defined as follows,

$$c_p(x) = \{p(x) - p_1\} \Big/ \frac{1}{2}\rho \bar{u}_1^2 \tag{1}$$

where the suffix 1 indicates the entrance section of the diffuser part and $\bar{u}_1$ represents area averaged mean velocity at the section. In reality we used the value $\bar{u}_o$ insted of $\bar{u}_1$. In the case of usual diffuser, an ideal pressure recovery coefficient $c_{pi}(x)$ is rather simply defined and is expressed in terms of the area ratio as,

$$c_{pi}(x) = 1/[1 - \{A_1/A(x)\}^2] \tag{2}$$

For the diffuser of this research, the ideal pressure recovery coefficient is not so simple as Eq. (2), because the energy is lost from the diffuser with sucked air. We assume that the suction velocity u_q and the suction pressure p_q are uniform in the transverse direction. Also the time averaged mean velocity and the pressure are assumed to be constant over the entire section considered. From the assumptions the energy equation reduces to

$$\left(\frac{1}{2}\rho u_0^2+p_0\right)u_0A_0=\left\{\frac{1}{2}\rho u(x)^2+p(x)\right\}u(x)A(x)+2\iint\left\{\frac{1}{2}\rho u_q(x)^2+p_q(x)\right\}u_q(x)da \tag{3}$$

, where the integration is performed over the surface of porous plate.

We meet a difficulty when we want to use Eq. (3), that is, to determine $u_q(x)$ and $p_q(x)$ is almost impossible for the real diffuser. Then we are compelled to make a rather crude approximatmation, $u_q(x)$ and $p_q(x)$ are constant and equal to $\bar{u}_q$ and $\bar{p}_q$ respectively, where $\bar{u}_q$ and $\bar{p}_q$ are averaged value in some sense. We define a reference pressure recovery cefficient $c_p'(x)$ as follows:

$$c_p'(x)=\frac{p(x)-p_1}{\frac{1}{2}\rho u_0^2}=\frac{1}{\frac{1}{2}\rho u_0^2u(x)A(x)}\left[\frac{1}{2}\rho u_0^3A_0+(p_0-p_1)u_0A_0-\frac{1}{2}\rho u(x)^3A(x)-\{\rho\bar{u}_q^2+2(\bar{p}_q-p_1)\}\bar{u}_q\iint da\right] \tag{4}$$

In the diffuser part $A(x)$ and the integration are

$$A(x)=h\{b_0+2(x-x_1)\tan\theta\},\quad \iint da=b_0(x-x_1')+(x-x_1)^2\tan\theta \tag{5}$$

The continuity equation reduces to

$$u(x)A(x)=u_0A_0-2b_0(x-x_1')\bar{u}_q-2\bar{u}_q\{b_0(x-x_1')+(x-x_1)^2\tan\theta\} \tag{6}$$

where x_1' denotes the position of the upstream edge of the porous plate. In the other parts of the passage, the forms to which these equations reduce are evident.

In the application of Eq. (4), $\bar{u}_q$ is determined from the measured suction volume, and the effective area of the porous plate which is calculated from porosity of the material of the porous plate. $\bar{p}_q$ is taken as a mean, $(p_{x_1'}+p_{x_2})/2$, where $p_{x_1'}$ and p_{x_2} are measured value of the static pressure at x_1' and x_2, at the rear edge of the porous plate. p_1 was determined by extension of hydraulic gradient of the inlet section to x_1, which was measured using straight duct without diffuser.

In order to estimate the effectivess of the suction for the diffuser performance of various geometry, we define following two pressure recovery coefficients.

$$C_{p1}=(c_p)_{max}/(c_p')_{max},\quad C_{p2}=(c_p)_{max}/(c_{pi})_{max} \tag{7}$$

These definitions are very simple but illustrative for the comparison of the effectiveness.

3. Experimental Results and Discussions

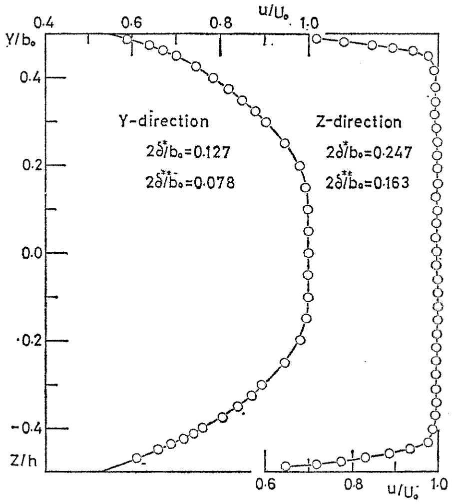

Fig. 2. Velocity distributions in the inlet section.

Velocity distributions at the section of $x/b_0 = -6.25$ are shown in Fig. 2. Mean velocity is 22.5 m/s and the values of displacement thickness and momentum thickness in both directions are presented in the figure. As clearly seen from the figure, spanwise, that is z-directional velocity distribution is constant over 80% of the inlet channel, so it may be said that the inlet flow has sufficient two-dimensionality.

After confirming the uniformity of the inlet flow, rather large amount of various measurements were performed. Analysis of the data showed that the characteristics of the diffuser used in this research might be clasified into three types, the gradual type, the step-gradual type and the step type. The gradual type means that the process of pressure recovery is gradual in the downstream direction and there is no appreciable stall region or if it may exist but only occasionally. The step type means that the pressure recovery curve has a step in the course of pressre increase. In the case of step-gradual type the pressure recovery curve has a step without suction and changes to the gradual type with suction. For the sake of clarity, we will describe mainly the typical cases of former two-types in what follows, that is the cases of $2\theta = 20°$ and the area ratio is 2 and 4.

3. 1. Velocity Distributions and their Change with Suction

A typical case of the gradual type is the case of area ratio $AR = 2$. The velocity distributions in the transverse direction are presented in Fig. 3 and in Fig. 4. The development of the flow field without suction is presented in Fig. 3, where the profiles are expressed in non-dimensional value with respect to the maximum velocity in the inlet channel.

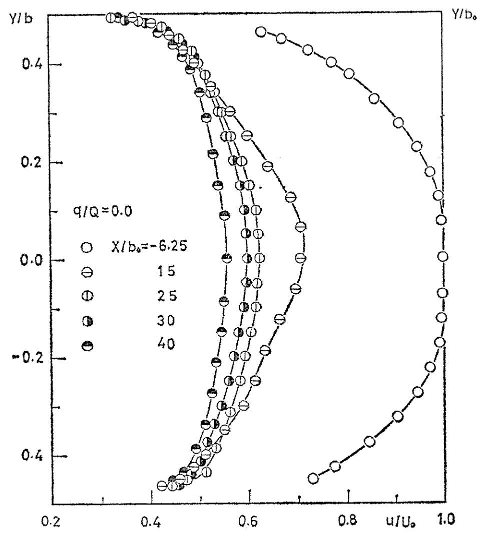

Fig. 3. Velocity distributions in the transverse direction without suction, $2\theta=20°$, $AR=2$.

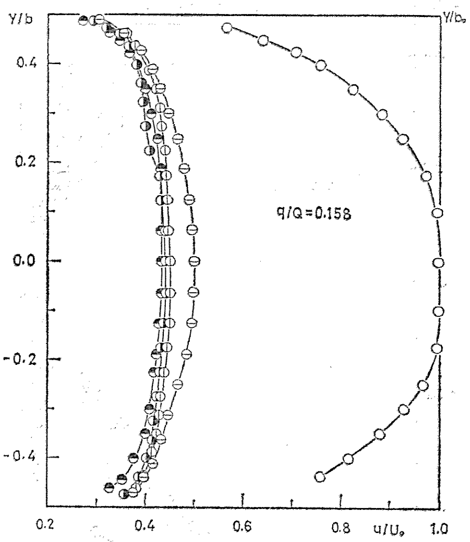

Fig. 4. Velocity distributions in the transverse direction with suction, $2\theta=20°$, $AR=2$, designation of marks is the same to Fig. 3.

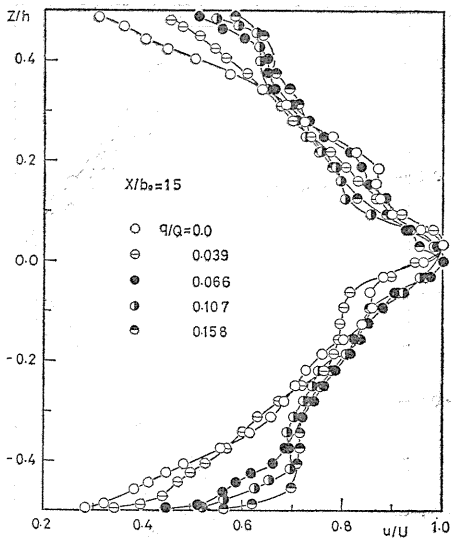

Fig. 5. Variation of the spanwise velocity distribution with suction at $x/b_0=15$, $2\theta=20°$, $AR=2$.

At the section $x/b_0=15$, near the end of the diffuser part, the velocity distribution shows a peak at the center. The flow diverges and fills up the channel in the downstream sections. From these measurements, it may be inferred that in this diffuser flow there is no stall region or if it exists, only temporary. When the suction is applied, the flow diverges slightly quicker than in the case of no suction as shown in Fig. 4. Comparison Fig. 3 and Fig. 4 indicates that the suction performed even through parallel wall is effective for the flow in the diverging region.

The effect of the suction on the velocity profiles is clearly seen in the spanwise direction as expected. Fig. 5 to Fig. 7 present the spanwise velocity distributions at the sections $x/b_0=15$, 25, 40, where the parameter is volumetric suction ratio q/Q as indicated in Fig. 5. Velocity distributions have a sharp peak in the center. In the case of without suction, the very sharp peak appears as shown in Fig. 5 and gradual spread of the flow occurrs in the downstream sections. When the suction is applied, velocity near the wall increases and the flow fills up the channel showing two-dimensionality in the pressure recovery regien.

Typical velocity distributions measured in the case of step type will be presented in what follows. Fig. 8 to Fig. 10 show transverse velocity distributions in the diffuser of area ratio 4. In this case flow pattern varies drastically between without suction and with suction. In Fig. 8 the velocity distribution without suction at the section of $x/b_0=15$, which lies in the pressure recovery region, shows no reverse flow, so it may be inferred that in the diffuser part, there is no stall region or only temporary stall if it may exist. But when the suction is applied, as clearly seen in Fig. 9, the flow becomes very unstable and reverse flow occurrs. The reverse flow region appears the other wall side with the increase of suction as shown in Fig. 10. In the pressure recovery region, $x/b_0=25$, the flow fills up the

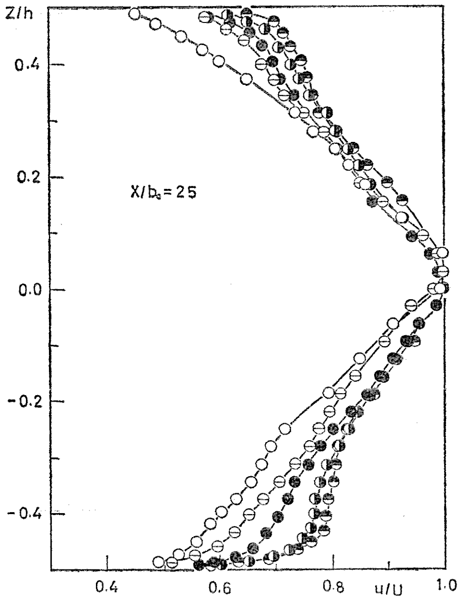

Fig. 6. Variation of the spanwise velocity distribution with suction at $x/b_0=25$, $2\theta=20°$, $AR=2$, designation of marks is the same to Fig. 5.

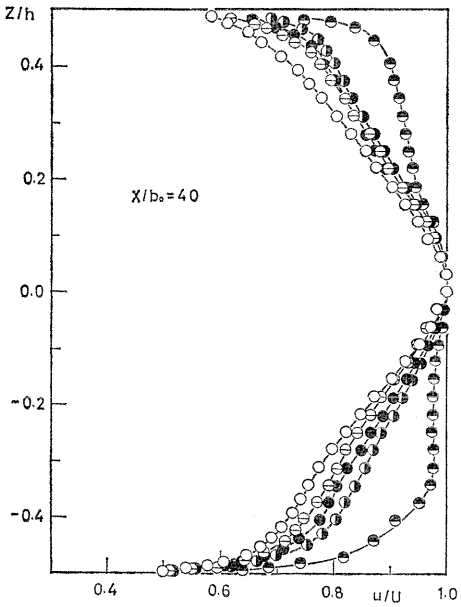

Fig. 7. Variation of the spanwise velocity distribution with suction at $x/b_0=40$, $2\theta=20°$, $AR=2$, designation of marks is the same to Fig. 5.

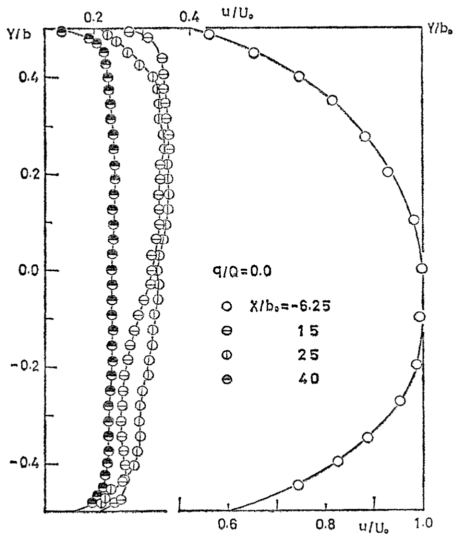

Fig. 8. Development of the transverse velocity distribution without suction, $2\theta=20°$, $AR=4$.

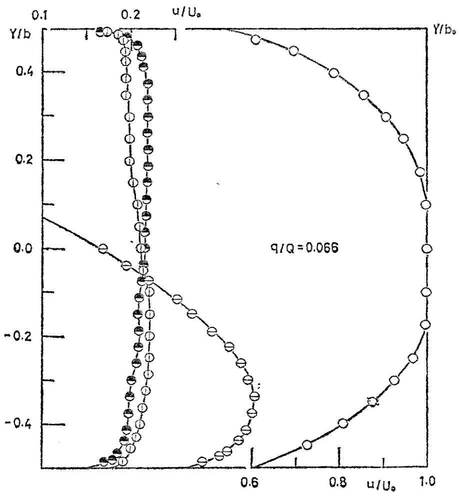

Fig. 9. Large variation of the velocity distributions in the transverse direction with suction $q/Q=0.066$, $2\theta=20°$, $AR=4$, designation of marks is the same to Fig. 8.

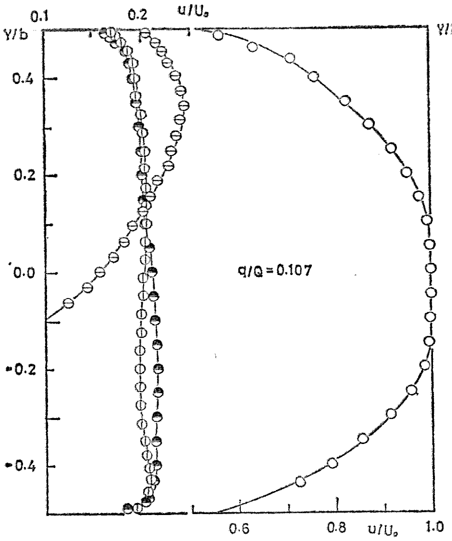

Fig. 10. Variation of the transverse velocity distribution with suction, $q/Q=0.107$, $2\theta=20°$, $AR=4$, designation of marks is the same to Fig. 8.

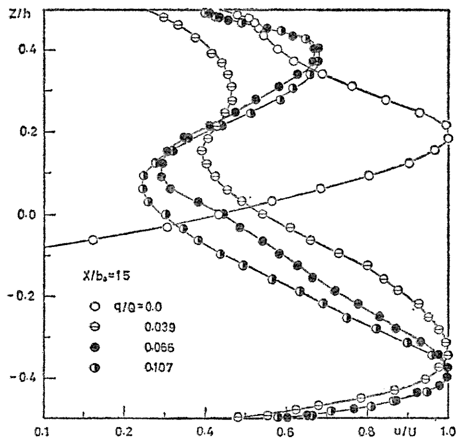

Fig. 11. Wall jet type flow in the spanwise direction at $x/b_0=15$, $2\theta=20°$, $AR=4$.

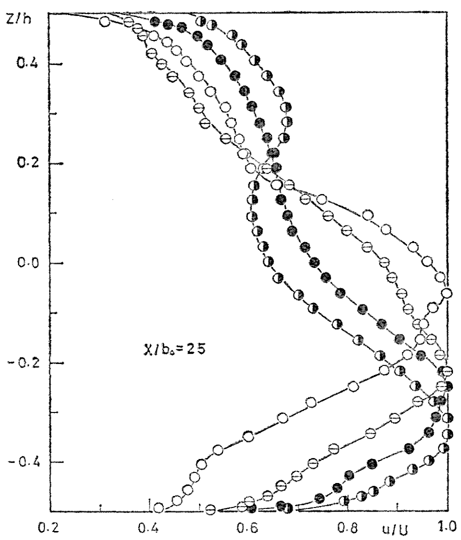

Fig. 12. Deflection of flow in the spanwise direction with suction at $x/b_0=25$, $2\theta=20°$, $AR=4$, designation of marks is the same to Fig. 11.

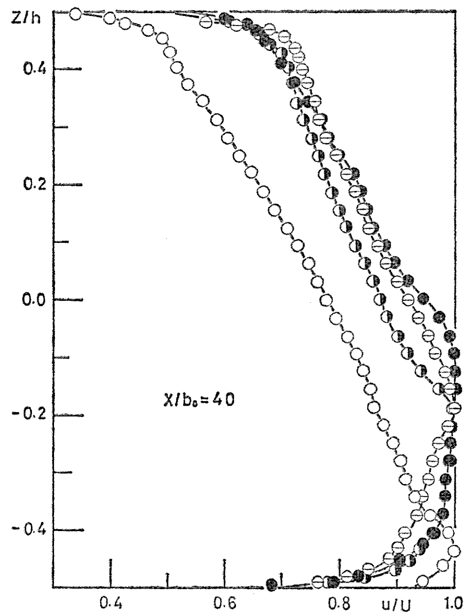

Fig. 13. Variation of the spanwise velocity distribution with suction at $x/b_0=40$, $2\theta=20°$, $AR=4$, designation of marks is the same to Fig. 11.

channel and becomes stable.

The spanwise velocity distributions in this case are presented in Fig. 11 to Fig. 13. The flow in the case of without suction shows a reverse flow region at the pressure recovery section $x/b_0=15$, and deflection of the flow pattern remains rather long distance in the downstream direction. Comparison of Fig. 8 and Fig. 11 indicates that the reverse flow occurrs not on the diverging wall side but on the parallel wall side on the contrary to the intuition. The suction applied through porous parallel wall sucks out the reverse flow region and velocity distributions appeared in Fig. 11 are akin to the flow field constructed from two wall jets on parallel walls having two velocity maxima near the parallel walls and a velocity minimum at the center of the duct. The phenomenon may be explained by considering the low pressure near the porous plate which induces the deflection of streamline and then Bernoulli equation shows the increase of velocity. In the downstream section flow pattern deflects on the one wall side as seen in Fig. 12. The deflection remains long distance and two-dimensionality of the flow field recovers very gradually as indicated by the velocity distributions at the section $x/b_0=40$ in Fig. 13.

It was a remarkable fact in the case of $AR=4$ that if the flow pattern shows two wall jets type, then if the suction is applied, there was almost always a reverse flow region on the one of the diverging wall side. This flow pattern is a feature of the step type.

3. 2. The Static Pressure Distributions and Relationships between them and Velocity Distributions

One of the most important diffuser performance is expressed by the process of pressure recovery. In Fig. 14, curves show pressure distributions along x-axis measured by static pressure holes on both parallel walls in the case of area ratio 2. Chain lines in the figure are calculated by Eq. (4) which repressent reference pressure recovery coefficient c_p' accounting for the suction. The dotted region over the abscissa and the short broken line on the abscissa show the porous suction plate and the outlet position of the diffuser part respectively.

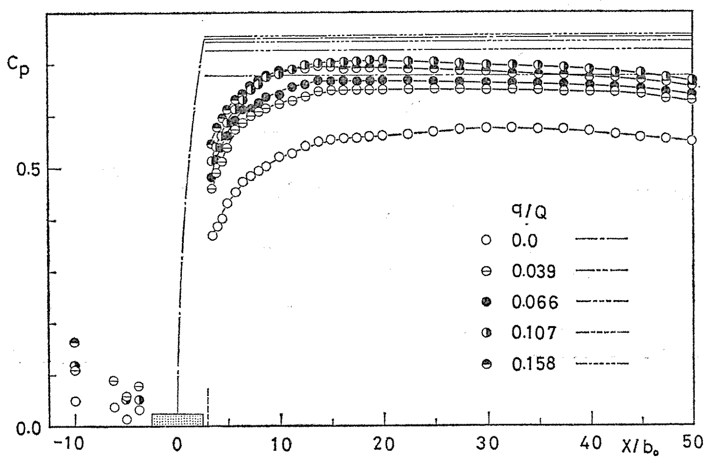

Fig. 14. Gradual type pressure recovery process. $2\theta=20°$, $AR=2$.

In this diffuser, $2\theta=20°$, $AR=2$, measured points show gradual increase of the static pressure irrespective of the value of volumetric suction ratio, so we call this type as gradual type. It was observed that the gradual pressure recovery process existed only when the stall region appeared neither on the parallel wall sides nor the diverging wall sides. When the suction is applied, the pressure recovery coefficient increases with the increase of the value of volumetric suction ratio as seen in Fig. 14. The phenomenon may be explained by the fact that the flow spreads in the duct due to the suction in both directions, the spanwise and the transverse, as shown in Fig. 4 and Fig. 5.

Fig. 15 represents the pressure recovery processes in the case of $2\theta=20°$, $AR=4$. Irrespective of the suction, the pressure recovery processes in this diffuser flow show stepwise increase. Especially the pressure in the case of without suction obtains one maximum value at the outlet of the diffuser and once decreases and then increases again. The velocity distributions in the duct show the reverse flow region at least one wall side, that is, on the parallel wall side or on the diverging wall side. For example, it is seen in Fig. 9 and in Fig. 11. The flow in the diffuser without suction separates from the both parallel walls and then the pressure recovery curve indicates a stepwise increase. The application of suction improves the value of pressure recovery coefficient and although the stepwise recovery can not be remedied but the process is shortened in the streamwise direction. This is due to the movement of the stall region with the suction from the parallel wall sides to the diverging wall sides.

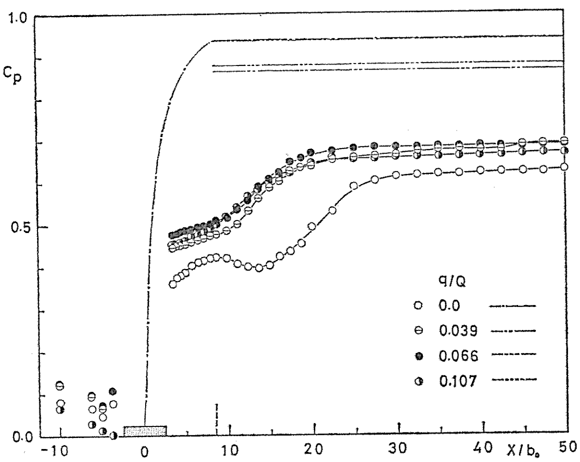

Fig. 15. Step type pressure recovery process, $2\theta=20°$, $AR=4$.

The suction eliminates the step in the pressure recovery process in such a case of $2\theta=10°$, $AR=3$ as shown in Fig. 16. If no suction is applied, the flow separates from the parallel walls of the diffuser part and a step appears in the pressure recovery curve. These stall regions are sucked out by the suction and the step of the presure recovery curve disappears as seen in Fig. 16.

The effectiveness of the suction on the pressure recovery process may be appreciated by C_{p1} or C_{p2} defined by Eq. (7). Figs. 17a, b, c show the curves in

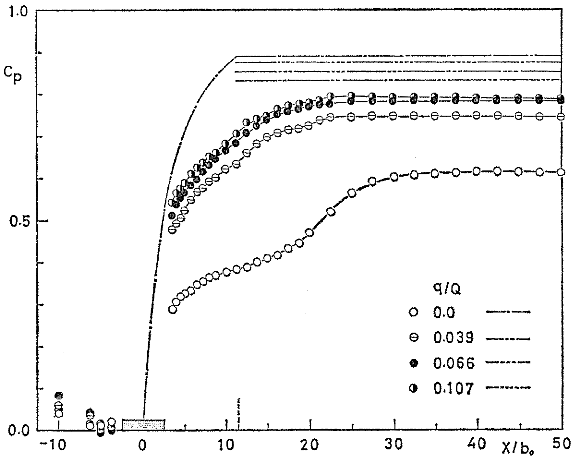

Fig. 16. Step-gradual type pressure recovery process, $2\theta=20°$, $AR=3$.

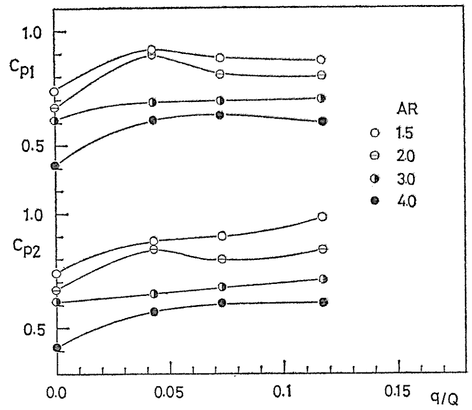

Fig. 17a. Variation of C_{p1} and C_{p2}, $2\theta=10°$.

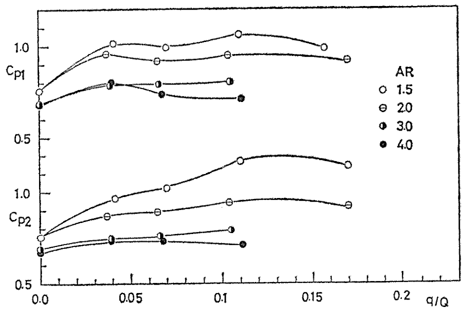

Fig. 17b. Variation of C_{p1} and C_{p2}, $2\theta=20°$.

the cases of $2\theta=10°$, $20°$, $30°$ respectively. It should be noted that according to the definition the value of C_{p1} or C_{p2} might become larger than 1. Although these figures should be considered as representing relative effectiveness of the suction among various cases, evidently the value of q/Q which needs obtaining maximum of C_{p1} is about 0.04.

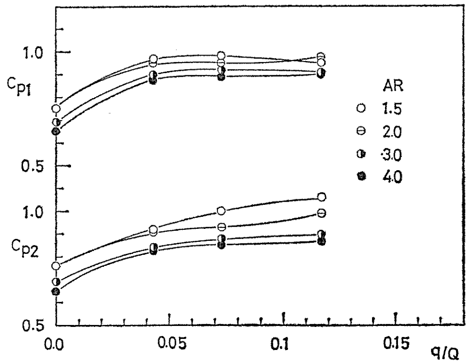

Fig. 17c. Variation of C_{p1} and C_{p2}, $2\theta=30°$.

3. 3. *Flow Visualization by use of Tufts*

It is important to grasp globally and intuitively the change of flow pattern in various fluid machinery. But since to obtain the entire flow pattern by use of the calculation or measurement using various probes is almost impossible, then flow visualization is a very useful tool in the study of fluid mechanics. Significant behaviour of the flow near the wall in the diffuser is most easily discernible by use of tufts. We attached a large number of cotton tufts through needles on the diffuser wall and sketched their movement in various cases.

A classification of tuft movement is presented by Kline et al. [8] and also it is used in this study. For the sake of convenience we will describe them in what follows. S: Steady turbulent flow — tuft points downstream with only small amplitude oscillations. U: Unsteady flow — tuft points downstream with medium amplitude oscillations. TI: Incipient transitory stall — tuft points downstream with large amplitude oscillations (tuft is on urge of pointing upstream). IT: Intermittent transitory stall — tuft points upstream for short periods of time and when pointing downstream, displays large amplitude oscillations. T: Transitory stall — tuft points upstream for approximately the same period of time as it points downstream. F: Fixed stall — tuft points upstream for long periods of time. The correspondence between these descriptions and arrow marks appeared in Figs. 18a and 18b is evident.

Figs. 18a, b represent schematic sketches of tufts movement and various flow regions in the case of $2\theta=20°$, $AR=4$, according to the above mentioned classification. Four walls of the diffuser are developed on to one plane. Fig. 18a shows flow field without suction. There is a large stall region on the lower parallel

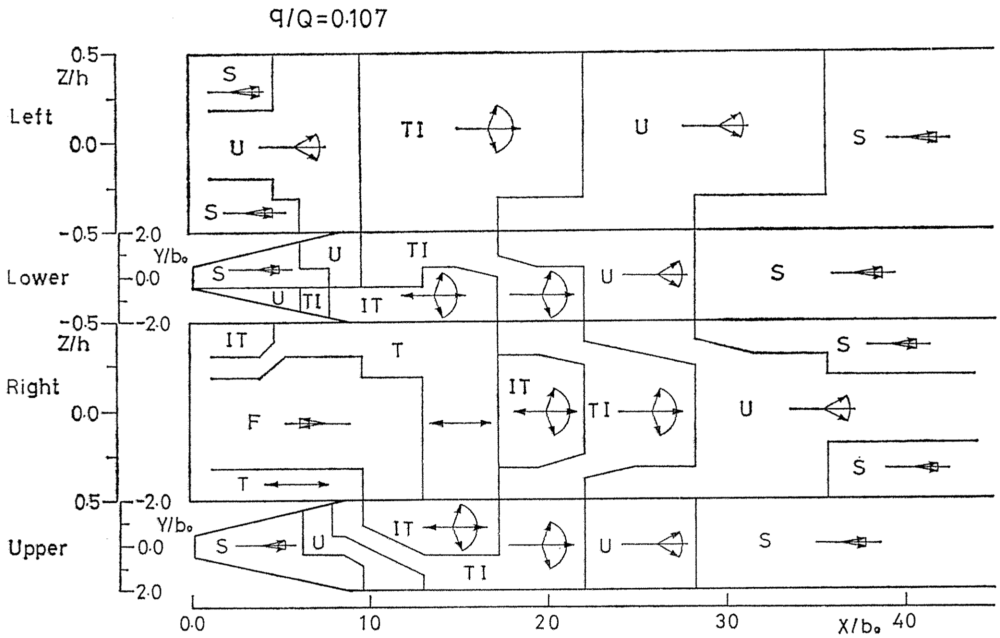

Fig. 18a. Flow pattern in the diffuser without suction, $2\theta=20°$, $AR=4$.

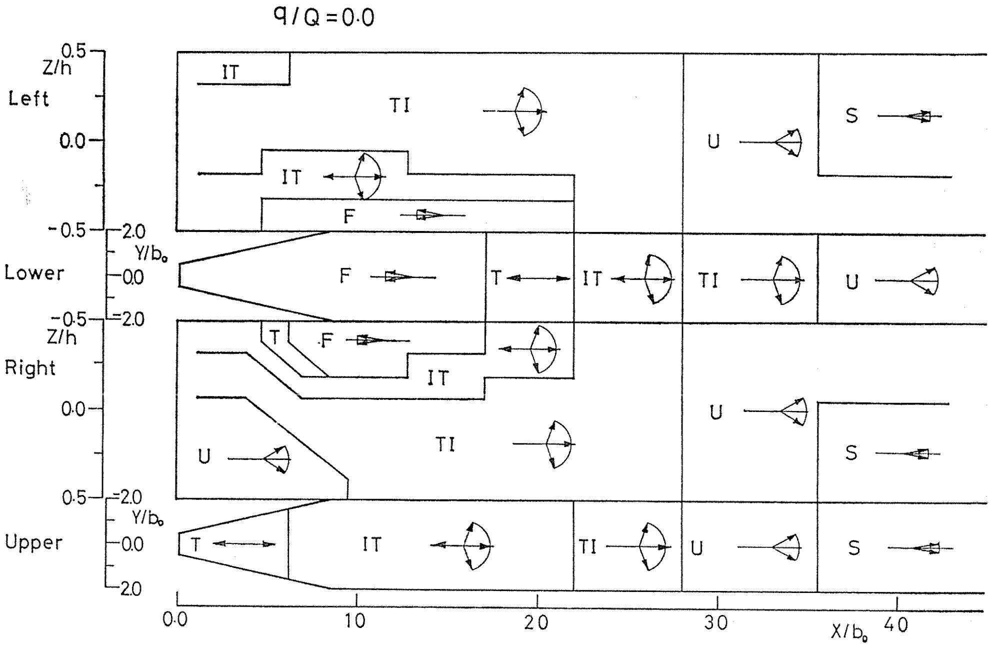

Fig. 18b. Flow pattern in the diffuser with suction, $2\theta=20°$, $AR=4$.

wall in the diffuser part and it elongates into the pressure recovery duct. On the upper parallel wall, there is an intermittent transitory stall region. On the each diverging wall side a small stall region exists near the lower parallel wall at the outlet section of the diffuser part.

The execution of the suction varies flow pattern as shown in Fig. 18b. The large stall region existed in the case of no-suction, as described above, vanishes by the suction. But a large fixed stall region appears on the right-hand diverging wall. It is concluded that the flow in this diffuser $2\theta=20°$, $AR=4$ can not completely attach on the wall irrespectively whether the suction is applied or not. We observed that the fixed stall region was stable in one experimental run but sometimes it varied its position in the other run.

4. Concluding Remarks

Experiments were performed on the velocity distributions and performance of the diffuser which has two porous suction plates on the parallel wall sides. The diffuser geometry and volumetric suction ratio were varied rather wide range. From a plenty of experimental data, some particular features were induced.

First, the suction even though applied on the parallel wall of the diffuser can improve appreciably the process of pressure recovery. Second, the pattern of the process of pressure recovery is classified into three kinds, that is the gradual type, the step type, and the step-gradual type. In the case of gradual type, the pattern of pressure recovery does not change without suction or with suction, but the value of pressure recovery coefficient increases with suction. In the case of step type, the pressure recovery curve has a step and it does not vanish with suction but still the value of pressure recovery coefficient increases with suction. The last type is the step-gradual type, that is the pressure recovery process changes from the step type to the gradual type with suction. Third, the flow pattern changes corresponding to the above mentioned types. It was remarkable in the case of the step type, the fixed stall region does not vanish but only changes its position with suction. The fixed stall region disappeared in the case of step-gradual type with suction.

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