Control of Separation in a Conical Diffuser by Vortex Generator Jets*

Michihiro NISHI**, Kouichi YOSHIDA**
and Keisuke MORIMITSU***

To develop a vortex-generator-jet (VGJ) method for separation control an experimental study was carried out using a 14 deg conical diffuser with and without VGJs. Static pressure recovery coefficient and a coefficient for loss of total pressure were both used as criteria to evaluate the effectiveness of several VGJ arrangements where two geometric parameters, jet-hole-size and the number-of-jets, were varied. It was found that VR (ratio of jet speed to freestream velocity) rather than Qj/Qm (ratio of jet flow-rate to total flow-rate) is more useful as a key parameter to understanding the control of the separation in a diffuser because the effects of change of geometrical parameters tend to be reduced. The total pressure losses were reduced by increasing VR up to values near 1.5 to 2.0 where losses reached a minimum. Due to the increasing losses associated with the production of the jets, total pressure losses increase with further increase of VR beyond 2.0.

Key Words: Flow Control, Diffuser, Separation, Vortex Generator Jets, Pressure Recovery Coefficient, Loss Coefficient

1. Introduction

A vortex-generator-jet (VGJ) is a pitched and skewed jet which issues from a small hole into a flow over a solid wall. The jet generates a single streamwise vortex which remains close to the wall, and extends many jet-hole diameters downstream⁽¹⁾. Just as in the case of solid vortex generators, it is expected that induced streamwise vortices which remain near the wall will promote turbulent mixing in the boundary layer and prevent the flow from separating. Since jet flow rate can be readily adjusted by an actuated valve when necessary, the VGJ method has the potential to be used in active control of separation on wings and in diffusers. The VGJ was introduced as a passive control device by Wallis⁽²⁾ almost 40 years ago, but very few studies have been made concerning

the VGJ method in comparison to work devoted to the separation control technique which uses solid vortex generators. Even the mechanism of the vortex generation by a skewed and pitched jet is yet to be understood, in detail.

Using a two-dimensional diffuser, Johnston & Nishi⁽¹⁾ demonstrated experimentally that a spanwise array of skewed and pitched jets issuing from jet-holes in the wall generated streamwise vortices and the vortices were effective in the control of separation of a turbulent boundary layer. Lin et al.⁽³⁾ succeeded in controlling two-dimensional turbulent flow separation over a backward-facing ramped step using VGJs, speed of which was 6.8 times the freestream velocity ($VR=6.8$). Here, for reasons yet to be understood, VR was much higher than required to control separation in Johnston & Nishi⁽¹⁾. To quantify the properties of a streamwise vortex generated by a pitched and skewed jet in a crossflow, Compton & Johnston⁽⁴⁾ measured the mean velocity field downstream of the jet in the test range, $VR=0.7$ to 1.3. Honami et al.⁽⁵⁾ investigated the behavior of laterally injected jets by using a hot-wire anemometer and a thermo-resistance meter to examine their film-cooling effectiveness.

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** Mechanical Engineering Department, Kyushu Institute of Technology, Sensui-cho 1, Tobata, Kitakyushu 804, Japan

*** Graduate School, Mechanical Engineering Department, Kyushu Institute of Technology, Sensui-cho 1, Tobata, Kitakyushu 804, Japan

Many other studies have been carried out in the field of film cooling⁽⁶⁾, since discrete jet injections, often used for cooling of gas turbine components, create complex flow behavior on the surface. Though those results are basically useful to understand some facets of interaction phenomena between jets and boundary layer, further studies from the viewpoint of shear layer control are also necessary to develop the VGJ technique.

Nishi et al.⁽⁷⁾ examined the applicability of VGJs to suppress the separation in a conical diffuser with a 14 deg. divergence angle, an inlet diameter of 125 mm, and area-ratio of 2.56 from inlet to exit plane. In their investigation, they mainly studied the effect of velocity ratio in the range, $VR=0$ to 1.9. A VGJ assembly at diffuser inlet was used. It had eight holes of 6 mm dia., each inclined at an angle of 30 deg (= pitch angle) to the surface and arrayed along the wall of the inlet pipe in the circumferential direction. All the holes were skewed in the same direction at 90 deg. Improvement of the diffuser performance was achieved even at low values of velocity ratio, $VR \geq 1$. Pressure recovery coefficient reached 0.68 for the $VR=1.9$ case, a value which was 0.05 greater than the base case without jet flow, $VR=0$.

The effectiveness of VGJs for separation control has been generally verified in several experiments, but much is still unknown. For example, what is the best geometric configuration of VGJs for optimum control of separating flow in a diffuser, and also, how is separating boundary layer flow in a diffuser influenced by those jets? Thus, as a continuation of the former study⁽⁷⁾, the present experimental study was conducted to clarify the effects of several major parameters needed for VGJ design on the separation in, and performance of a conical diffuser.

Nomenclature

- A : cross sectional area (m^2)
- C_p : pressure recovery coefficient of diffuser
- C_{pi} : C_p for an ideal, one dimensional flow
- C_{pz} : local static pressure recovery coefficient
- D : pipe diameter (mm)
- d : jet hole diameter (mm)
- n : the number of jets
- p : pressure (Pa)
- p_a : atmospheric pressure (Pa)
- Q_j : total flow-rate through jet holes (m^3/s)
- Q_m : flow rate through the diffuser (m^3/s)
- R : pipe radius (mm)
- Re : pipe Reynolds number
- $\bar{u}$: area-mean axial velocity (m/s)
- U : freestream velocity (m/s)
- V_j : central jet velocity at the hole (m/s)
- VR : velocity ratio of jet speed to the freestream
- z : axial distance from VGJs (mm)
- z'' : axial distance from the diffuser inlet (mm)
- δ^* : displacement thickness of boundary layer (mm)
- ρ : density (kg/m^3)

Subscript

- 1 : diffuser inlet

2. Experimental Apparatus and Method

The open-return test apparatus from earlier work⁽⁷⁾, see Fig. 1, was also utilized here. The VGJs assembly was placed below the inlet pipe, upstream of a conical diffuser. The assembly was the same internal diameter as the inlet pipe, $D=2R=125$ mm. The diffuser's dimensions are as follows: divergence angle=14 deg, total area ratio=2.56 from inlet to exit which would give an ideal pressure recovery coefficient (C_{pi}) of 0.847. This geometry is regarded

Fig. 1 Schematic Diagram of Test Apparatus (Inlet dia.: $D=2R=125$ mm)

Table 1 Experimental conditions

pitch angle	30 deg				
skew angle	90 deg (co-rotating type)				
hole diameter	6 mm	3 mm			
Diameter ratio, D/d	20.8	41.6			
number of jets, n	2	4	8	8	16
$(\pi D/n)/d$	32.7	16.4	8.2	16.4	8.2
velocity ratio, VR	2.5 ~ 3.5	1.5 ~ 3.5	0.4 ~ 3.5	2.6 ~ 3.4	1.6 ~ 3.6
δ^*/d	0.16	0.32

Fig. 2 Vortex generator jet hole

as a critical one which will separate upstream of the diffuser exit plane. It is located just above the Cp^* -line in the performance map from Miller's guide to design in "Internal flow"⁽⁸⁾.

The air used as vortex generator jets was diverted from the main flow from the fan through a bypass pipe located downstream of an orifice flowmeter. The orifice meter measured the total flow-rate, Q_m , through the diffuser. The bypassed flow-rate, Q_j , was measured with a rotameter before it entered the VGJs assembly.

Among VGJ geometrical quantities, the jet-hole-size, d , and the number of equally spaced jets, n , were the variable parameters in this study. With $d=3$ mm, $n=8$ and 16 were used, and at $d=6$, $n=2$, 4, and 8 were used. As shown in Fig. 2, all holes were drilled at a pitch angle of 30 deg and a skew angle of 90 deg, values which were adopted from their apparent effectiveness as shown in previous studies.

Separation in a diffuser causes performance to deteriorate. Diffuser performance may be measured in several ways. Two parameters were chosen here, the static pressure recovery coefficient, Cp , and the total pressure loss coefficient, ζ (see later section).

Static pressure recovery from inlet to exit is defined in the usual way by using the following dimensionless coefficient.

$$Cp = (p_a - p_1) / (\rho \bar{u}_1^2 / 2) \quad (1)$$

where $(p_a - p_1)$ is the static pressure rise, measured on the diffuser axis, and $\bar{u}_1$ is the area-mean velocity at

Fig. 3 Local pressure recovery coefficients versus the ideal ones for the 14 deg diffuser without VGJs

the diffuser inlet ($z''=0$). p_a , the atmospheric pressure, equals the diffuser exit pressure in this case where the diffuser exhausts directly into the atmosphere. Equation (1) also gives the local pressure recovery coefficient Cpz if pressure p in the diffuser is substituted for p_a . Center line pressure, p , was measured by traversing a small, straight tube of 3 mm dia. along the central axis of the diffuser. Small holes in the wall of the tube served as static pressure taps.

Table 1 summarizes the range of the present experiments where five kinds of VGJ arrangement were tested under the constant Reynolds number $Re = 8 \times 10^4$. The blockage factor $2\delta^*/R$ was 0.03 at the position of the jet-holes, which locates the axial position, $z=0$, a distance $0.56R$ (35 mm) upstream of the diffuser inlet.

3. Results and Discussion

3.1 Pressure recovery coefficient

Figure 3 shows the local pressure recovery coefficient Cpz plotted against the local ideal pressure recovery coefficient Cpi for the 14 deg conical diffuser without VGJs. Since the inlet blockage was small, the static pressure recovered effectively toward downstream and it is suspected that separation in the diffuser was not very serious. The diffuser effectiveness in this case reaches $Cp/Cpi = 0.63/0.847 = 0.74$.

Figure 4 shows the pressure recovery coefficient C_p of the diffuser plotted against the velocity ratio $VR = V_j/U$ for the five VGJ arrangements described in Table 1. The solid square at $C_p = 0.63$ shows the pressure recovery for the diffuser without VGJs. The following features are observed in this figure.

1. Improvement of C_p is achieved by application of VGJs when VR is greater than 1.
2. C_p increases with VR for every VGJ arrangement.
3. For the large jet-hole cases ($d=6$ mm), C_p increases as the number of VGJs increases at constant VR .
4. The opposite trend is observed for the small jet-holes ($d=3$ mm). Namely, C_p for $n=16$ is smaller than that for $n=8$.
5. Except for one case ($d=3$, $n=16$), C_p values are nearly identical up to $VR=2.5$.
6. In a particular case ($d=6$, $n=8$), the highest values of C_p are achieved for all velocity ratios in the range where comparisons are possible, above $VR=1.5$.

Fig. 4 The effect of VR on C_p of the 14 deg diffuser with VGJs

Fig. 5 The effect of Q_j/Q_m on C_p of the 14 deg diffuser with VGJs

In order to examine the effect of jet flow-rate, the experimental C_p data was plotted versus the fraction of jet flow-rate to total flow-rate Q_j/Q_m in Fig. 5. From this, additional features are recognized:

7. C_p generally increases with Q_j/Q_m .
8. At constant Q_j/Q_m , C_p improves as the number of jets decreases.
9. The narrow spread of the data in Fig. 4 compared to Fig. 5 indicates that VR rather than Q_j/Q_m may be a more useful parameter for design to reduce flow separation effects in a diffuser.

C_p generally approaches a maximum at the condition where the separation in the diffuser is fully suppressed. However, here C_p continues to increase as VR increases after separation is already substantially eliminated. In order to examine the cause of this continuous increase in C_p the local pressure distribution, C_{pz} , was measured in the diffuser having the ($d=6$, $n=8$) jet-arrangement, and when the VGJs were operating at peak velocity, $VR=3.5$. The result is shown in Fig. 6, where the distribution without VGJs is also shown for comparison. Compared to the latter distribution, a small, but abrupt increase of pressure occurs between the last point upstream of the exit and the exit plane point ($z''/D=2.44$). The value of C_{pz} at the exit plane is set at atmospheric pressure, p_a , the pressure in the large room into which the diffuser exhausts. This final, abrupt pressure rise occurs in the diffuser exit region as the flow expands into the room. The reduced pressure along the diffuser axis, where the pressure probe is traversed, must be caused by the layer of swirling flow close to the wall. This swirl is induced by the tangential velocity components created by the skewed jets. The excess dynamic pressure (relative to the core flow) in this jet-induced swirling layer is partially recovered, and consequently C_p continues to increase as VR

Fig. 6 Distribution of pressure recovery along the center axis of 14 deg diffuser with VGJ-arrangement ($d=6$, $n=8$) operating at $VR=3.5$

increases even after the separation is completely suppressed.

Concerning the opposing trends noted in items 3 and 4, the trend noted in 3 is understandable, because increasing the number of vortices along a given spanwise distance should be favorable for suppression of separation in a diffuser. The opposite trend noted in 4 is thus anomalous, and therefore it is suspected that the process of interaction between vortices and the boundary layer in the case of VGJ-arrangement ($d=3, n=16$) is somehow different. Further study, beyond the scope of this work, is needed to resolve the question raised in item 4.

3.2 Loss coefficient

Since additional power is required to increase VR and/or Qj/Qm , energy consumption in the diffuser flow should be another measure for the selection of a desirable VGJ arrangement. The loss coefficient for a downstream diffuser with VGJs is derived from the law of total energy conservation. This law is approximated by the equation shown below by assuming steady state, one-dimensional flow in each stream that enters and leaves the system, and no recovery of the exit kinetic energy from the diffuser :

$$p_1 + \frac{Qm - Qj}{Qm} \cdot \frac{\rho}{2} \left(\frac{Qm - Qj}{A_1} \right)^2 + \frac{Qj}{Qm} \cdot \frac{\rho}{2} \left(\frac{Qj/n}{A_j} \right)^2 = p_a + \Delta p \quad (2)$$

where Δp denotes the pressure loss of total pressure between the diffuser inlet and the stagnant atmosphere. The loss coefficient ζ is given by

$$\zeta = \Delta p / (\rho u_1^2 / 2) = (1 - Qj/Qm)^3 + (D/d)^4 (Qj/Qm)^3 / n^2 - C_p \quad (3)$$

From this equation, by use of the data, we calculated the loss coefficient ζ and plotted it against VR and Qj/Qm in Fig. 7 and 8 respectively. As shown in both figures, a reduction of ζ is accomplished by using VGJs in limited ranges of VR and Qj/Qm . At low values of either parameter the loss coefficient decreases as they increase, but the trend reverses in the higher range of VR and Qj/Qm , and the loss coefficient increases to very high values which are above the basic value of ζ when there is no jet flow.

The initial reduction of the total pressure loss coefficient may be attributed to the reduction of flow blockage associated with elimination of regions of separated flow. However, as flow rates and jet velocities increase, the losses of kinetic energy associated with the injected flow become larger very rapidly (e.g., for $Qj/Qm \ll 1$, approximately as the third power of Qj/Qm), and overpower the savings resulting from separation control.

Comparing the results in Fig. 7 to those in Fig. 8 shows that the velocity ratio, VR , is less sensitive to geometrical arrangement in that minimum loss occurs

Fig. 7 The effect of VR on ζ of the 14 deg diffuser with VGJs

Fig. 8 The effect of Qj/Qm on ζ of the 14 deg diffuser with VGJs

for all cases in the range of $1.5 < VR < 2.0$. When the data is plotted versus Qj/Qm , it is less clear where the optimum value of Qj/Qm lies for a given geometric arrangement. In any case, for minimum loss, the values of Qj/Qm were small.

4. Concluding Remarks

The present experimental study evaluated the effects of variation of several VGJ parameters on flow separation in a conical diffuser by measuring two performance parameters; the static pressure recovery coefficient and the total pressure loss coefficient. The conclusions from the study are:

1) Vortex generator jets may be used to suppress separation in a conical diffuser and to improve the pressure recovery and decrease the losses, a result which confirms and extends earlier work⁽⁷⁾.

2) Compared to the flow rate ratio, Qj/Qm , the ratio of jet speed to freestream velocity, VR , appears to be a more practical parameter to apply in the design of VGJs to control separation and reduce total pressure losses in a diffuser.

3) If the VGJ method is effective for separation control in a diffuser, the static pressure recovery increases continuously as VR is increased.

4) Diffuser total pressure losses are reduced for a VR range below a certain limit. In this experiment the values of VR for minimum loss lay in the range from 1.5 to 2.0. Use of VGJs with VR values higher than the limit leads to total pressure losses which can rise to very large values.

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