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Sensitivity of an asymmetric, three-dimensional diffuser to inlet condition perturbations

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ABSTRACT

The sensitivity of a three-dimensional, asymmetric diffuser to inlet condition perturbations was investigated using dielectric barrier discharge plasma actuators. Previous experimental and computational studies revealed the sensitivity of the separated flow in this diffuser to secondary flows in the inlet duct of the diffuser. By purposefully altering these secondary flows with highly tunable plasma actuators, the diffuser's pressure recovery could be both significantly improved and degraded. Two cases, one with pulsed forcing and another with continuous forcing, were selected for further study using 2D particle image velocimetry (PIV). PIV data were acquired in five streamwise-wall-normal planes. These measurements reveal that the relatively weak spanwise forcing introduced by the plasma actuators changes the size and orientation of the separation bubble. Pulsed forcing produces a strong peak in the Reynolds shear stress in the boundary layer upstream of separation. This significantly delays separation leading to a large increase in diffuser pressure recovery. In contrast, continuous plasma actuator forcing causes early separation on the diffuser sidewall, completely changing the separation geometry. This causes a larger and more unsteady separation bubble with higher reversed flow velocities which contribute to losses in the diffuser's pressure recovery.

1. Introduction

Diffusers are ubiquitous in engineering applications. Usually simple in design, they serve to increase the static pressure of a flow by reducing its velocity, albeit often with significant losses. The diffuser that is the subject of the present study was first examined experimentally by Cherry et al. (2008). It has a simple design, as illustrated in Fig. 1, but it develops complex three-dimensional flow features. Magnetic resonance velocimetry (MRV) was used to obtain a high resolution, three-dimensional, three-component mean velocity database. A stable separation bubble forms early in the expanding section of the diffuser and spreads across one of the two expanding walls of the diffuser. The flow eventually reattaches in a straight exhaust duct where further pressure recovery occurs. A comprehensive direct numerical simulation database (Ohlsson et al., 2010) corroborates the MRV experiments and provides more detailed information about the turbulence properties. Malm et al. (2012) utilized the temporal information from this DNS and investigated the low-frequency unsteadiness of the flow, as a low-frequency shedding of a structure was discovered in Ohlsson et al. (2010). Coherent large-scale motions with frequencies in a narrow band are thought to be sustained through a feedback mechanism, not dissimilar to that observed in a turbulent jet bounded by regions of separated flow (Malm et al., 2012). Additionally, they confirmed that the corner vortices that develop due to secondary flow in the inlet duct persist into the diffuser and evolve asymmetrically.

Because of its simple three-dimensional geometry and the existence of a high quality velocity dataset, this diffuser has become a popular test case for validating numerical simulations. Several computational studies have demonstrated the importance of correctly representing the secondary flows in the inlet duct. This sensitivity to inlet conditions suggested that the diffuser's performance could be significantly altered by purposefully perturbing the secondary flows in the inlet duct.

Grundmann et al. (2011) took advantage of this sensitivity by placing highly tunable dielectric barrier discharge plasma actuators on one wall of the diffuser's rectangular inlet duct. A wide range of perturbations was generated by varying the actuators' geometry, orientation and operating parameters. Configurations that produced spanwise forcing significantly altered the diffuser's pressure recovery. The actuators were operated in both continuous

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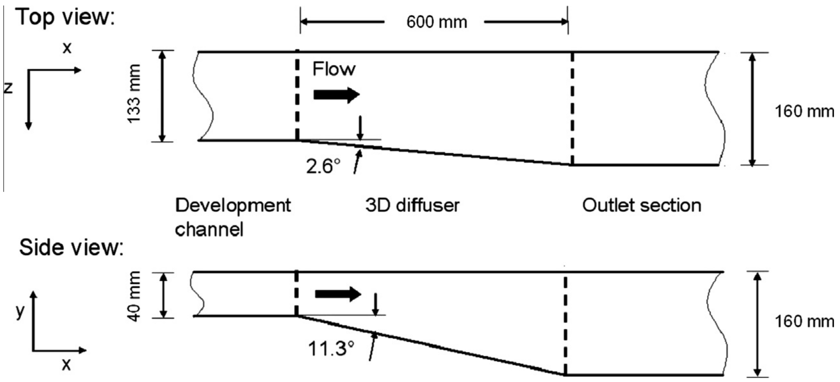

Fig. 1. Top and side views of the diffuser.

and pulsed modes with a wide range of duty cycle and modulation frequency combinations. Depending on the orientation, the wall-jets generated by the actuators could be directed either inwards, towards the centerline of the channel, or outwards, towards the corners. Improvements and degradations in pressure recovery as large as 20% relative to the baseline case were observed.

Detailed MRV measurements of these cases could not be replicated because the plasma actuators operate in air and the MRV experiments use water as the working fluid. However, because two of the cases of interest used continuous forcing, the effects on the diffuser's pressure recovery were replicated by placing small delta wing vortex generators in the inlet duct (Grundmann et al., 2012). MRV data reveal marked differences between the two vortex generator cases and the baseline case. Improved pressure recovery was associated with a smaller separation bubble and more uniform velocities at the outlet of the diffuser. The case which decreased the diffuser's performance showed a rapid growth of the separation bubble and the persistence of a high speed core throughout the length of the diffuser which was accompanied by significant in-plane velocities at the diffuser's outlet plane. The separation bubble in this case was fundamentally different from that in the other two cases, as it spread along the side expanding wall.

Passive manipulation of the secondary velocities in the inlet channel, analogous to vortex generators and steady plasma actuator forcing, was investigated computationally by Schneider et al. (2011). The baseline secondary flow in the diffuser's inlet cross-section is characterized by pairs of counter-rotating vortices located near the corners of the inlet duct. Schneider et al. (2011) conducted numerical experiments in which the baseline mean secondary velocities in the inlet plane of the diffuser were strengthened in either their natural rotation directions or against them. This manipulation served to redistribute streamwise momentum at the diffuser's inlet. When the vortices were strengthened in their natural sense of rotation, higher momentum fluid accumulated in the corners of the inlet duct. This surplus of momentum in the corners prevented the separation bubble from originating in the corner between the two expanding walls, as in the baseline case. Instead, the flow separated midspan on the more aggressively expanding wall and the separation bubble grew more slowly than in the baseline case, leading to a smaller separation bubble and an improved pressure recovery. In the opposite case, when the natural rotations of the mean secondary vortices were reversed, low momentum fluid was transported away from the corner between the two expanding walls. This resulted in a faster growing and overall larger separation bubble, which spread along the side expanding wall. In this case, the rapid growth of the separated flow region early on in the diffuser translated to higher overall losses. These numerical studies demonstrate how the manipulation of secondary velocities in the diffuser's inlet redistribute streamwise momentum, thereby changing the separation bubble's size, location and orientation. The growth of the separated flow region early on in the diffuser's expansion plays a critical role in determining the diffuser's overall pressure recovery.

Computational studies which focus on modeling the force imparted by the plasma actuators have been carried out by Maden et al. (2013). To test the model, these forces were incorporated into a computation of the baseline three-dimensional diffuser to replicate the experimental setup of Grundmann et al. (2011). Continuous spanwise forcing, directed towards the corners of the inlet channel, create wall jets which oppose the baseline motion of the secondary flow in the inlet channel. These simulations show good agreement with the experiments as they accurately predict the distribution of streamwise velocity at the diffuser's inlet and capture the separation behavior observed in the analogous MRV measurements. The simulation of the continuous forcing case shows flow separating along the side expanding wall, and the corresponding decrease in pressure recovery also agrees well with experimental data.

An open question that remains from the work of Grundmann et al. (2011) is why the pulsed plasma actuators have such a different effect on diffuser performance than continuously-operated actuators. They showed that continuously-operated actuators produced a strong degradation in the diffuser pressure recovery while the exact same actuators operated in a pulsed mode at Strouhal numbers near 0.032 produced large improvements in pressure recovery. Clearly the change in actuation changed the separation geometry, but it is not clear why this occurred.

Kolade (2010) built a 4× scaled-up version of the Cherry diffuser to acquire 2D PIV measurements augmenting the original MRV data. The goal of the present study is to use PIV measurements in this larger air-flow facility to understand how plasma actuators produce such large changes in diffuser performance, and in particular, why pulsing the forcing produces opposite results from continuous forcing. Furthermore, measurements of fluctuating velocity components will indicate the stability of the separation bubbles in the different configurations.

2. Experimental setup

The experiments were conducted in the Stanford High Reynolds Number Wind Tunnel with a 4:1 scaled-up model of the original test apparatus. The diffuser is fed by a fully-developed rectangular inlet duct with an aspect ratio of 3.33 and a Reynolds number of 26,000 based on a 40 mm channel height and a bulk velocity of 10 m/s. The diffuser has an area ratio of 4.8 as it expands from the rectangular inlet measuring 133 mm by 40 mm to a 160 mm by 160 mm square outlet. The expansion takes place over a length of 600 mm, corresponding to 15 channel heights. There are two

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