The evolution of initially uniform shear flow through a nearly two-dimensional 90° curved duct

H. J. Lim, M. K. Chung, H. J. Sung

Abstract An experimental study has been made in a nearly two-dimensional 90° curved duct to investigate the effects of interaction between streamline curvature and mean strain on the evolution of turbulence. The initial uniform shear at the entrance to the curved duct was varied by an upstream shear generator to produce five different shear conditions; a uniform flow (UF), a positive weak shear (PW), a positive strong shear (PS), a negative weak shear (NW) and a negative strong shear (NS). The variations of surface pressure and the mean velocity profiles along the downstream direction under different initial shears are carefully measured. The responses of turbulent Reynolds stresses and triple velocity products to the curvature and the mean strain are also investigated. The evolution of turbulence under the curvature with the different shear conditions is described in terms of the turbulent kinetic energy and the various length scales vs the angular distance θ or a curvature parameters Sc which is defined by Sc = (U/R)/(dU/dy) - U/R. The results show that the turbulent kinetic energy and the integral length scale are augmented when Sc < 0.054 whereas they are suppressed when Sc > 0.054. It is also observed that the micro-length scales of Taylor and Kolmogoroff are relatively insensitive to the curvature.

List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Cpw</td>
<td>wall static pressure coefficient, Cpw = 2(P - Pwall)/ρU²</td>
</tr>
<tr>
<td>D</td>
<td>duct width = 190 mm</td>
</tr>
<tr>
<td>d</td>
<td>turbulent diffusion</td>
</tr>
<tr>
<td>H</td>
<td>duct height = 600 mm</td>
</tr>
<tr>
<td>k</td>
<td>turbulent kinetic energy, k = (q²)/2</td>
</tr>
<tr>
<td>L</td>
<td>streamwise integral length scale or duct length</td>
</tr>
<tr>
<td>l</td>
<td>characteristic length scale</td>
</tr>
<tr>
<td>n</td>
<td>normal distance from curved surface</td>
</tr>
<tr>
<td>P</td>
<td>wall static pressure</td>
</tr>
<tr>
<td>Pwall</td>
<td>wall static pressure at x = 8D</td>
</tr>
<tr>
<td>Pwf</td>
<td>pressure fluctuation</td>
</tr>
<tr>
<td>R</td>
<td>radius of curvature</td>
</tr>
<tr>
<td>ReD</td>
<td>Reynolds number based on Uc and D, ReD = UcD/ν</td>
</tr>
<tr>
<td>S</td>
<td>ratio of curvature strain to straight mean strain, S = (U/R)/(dU/dy)</td>
</tr>
<tr>
<td>Sc</td>
<td>ratio of curvature strain to total mean strain, Sc = (U/R)/(dU/dy - U/R)</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>U, V, W</td>
<td>mean velocity components in x, y, z coordinates, respectively</td>
</tr>
<tr>
<td>U₁</td>
<td>centerline mean velocity at x = 8D</td>
</tr>
<tr>
<td>u, v, w</td>
<td>velocity fluctuations in x, y, z coordinates, respectively</td>
</tr>
<tr>
<td>u₁</td>
<td>characteristic velocity scale</td>
</tr>
<tr>
<td>u₁, v₁, w₁</td>
<td>Reynolds normal stresses in the x, y, z coordinates, respectively</td>
</tr>
<tr>
<td>u₁uv, u₁v₁w₁, u₁w₁v₁</td>
<td>Reynolds shear stress</td>
</tr>
<tr>
<td>x, y, z</td>
<td>triple velocity products</td>
</tr>
<tr>
<td></td>
<td>streamwise, transverse and spanwise coordinates</td>
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Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>δ</td>
<td>boundary layer thickness</td>
</tr>
<tr>
<td>ε</td>
<td>dissipation</td>
</tr>
<tr>
<td>η</td>
<td>Kolmogoroff micro-length scale</td>
</tr>
<tr>
<td>λ</td>
<td>Taylor micro-length scale</td>
</tr>
<tr>
<td>ν</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>φ</td>
<td>pressure-velocity correlation term</td>
</tr>
<tr>
<td>θ</td>
<td>flow angle in curved duct</td>
</tr>
<tr>
<td>ρ</td>
<td>density of air</td>
</tr>
<tr>
<td>τ</td>
<td>non-dimensional development time, τ = (x/Λ) [dU/dy]</td>
</tr>
<tr>
<td>τ₀</td>
<td>modified non-dimensional development time, τ₀ = (x/Λ) [dU/dy - U/R]</td>
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Subscripts

<table>
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<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>o</td>
<td>initial value at θ = 10°, y/D = -0.1</td>
</tr>
<tr>
<td>w</td>
<td>surface wall</td>
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1 Introduction

The effects of streamline curvature on turbulence have been intensively investigated both experimentally and theoretically due to the dramatic change in the turbulence structure under...
the stabilizing or destabilizing curvature. Most experimental studies have been carried out in turbulent boundary layers over a convex surface (So and Mellor 1973; Meroney and Bradshaw 1975; Ramaprian and Shivaprasad 1977, 1978; Muck et al. 1985), a concave surface (Meroney and Bradshaw 1975; So and Mellor 1975; Ramaprian and Shivaprasad 1977, 1978; Hoffmann et al. 1985; Barlow and Johnston 1988) or in a curved duct of high aspect ratio (Eskinazi and Yeh 1956; Ellis and Joubert 1974; Hunt and Joubert 1979).

A consensus among the experimental findings can be summarized as follows: The convex (or concave) curvature suppresses (augments) the diffusion of turbulent energy away from the wall, decreases (increases) drastically the intensity of turbulence, shear stress and skin friction, reduces (amplifies) the large scale motion normal to the wall and the length scale of turbulence and shifts the spectral distribution of turbulent energy toward high (low) wave number regions. Another characteristics of the curvature effects are that the velocity fluctuations parallel to the radius of curvature (\(v\)-component) are more strongly affected than those in the streamwise direction (\(u\)-component).

Hunt and Joubert (1979) discussed the effects of curvature on turbulence by investigating the governing equations in curvilinear \(s-n\) coordinates for the mean momentum and the Reynolds shear and normal stresses. The extra curvature strain \(\partial U/\partial R\) does not contribute any to the total turbulent kinetic energy production. Since an extra production term \(4\nu \partial U/\partial R\) appears in both the equations for \(Du/dt\) and \(Dv/dt\) with different sign, the extra strain is thought to produce an 'energy pump' effect by which some of the existing energy is transferred without any loss between the components in the plane of streamline curvature.

Another important contribution of curvature strain to turbulence is closely associated with the third-order terms in the Reynolds stress equations. The order of magnitude analysis reveals that the curvature terms in the third-order moments are scaled by \(q^3/R\) while other terms are scaled with \(q^3/l\), where \(q=(u^2+v^2+w^2)^{1/2}\) and \(l\) is the length scale. If the curvature is small or \(R/l\ll 1\), then the curvature terms are negligible. However, in the separated recirculating region of a backward-facing step or in the corner regions of a duct or cavity, for example, the magnitude of \(R\) has the same order as \(l\) and thus curvature term is comparable to other terms. Even in the curved boundary layer flows (\(\delta/R\approx 0.01\)), Ramaprian and Shivaprasad (1978) observed remarkable influence of the streamline curvature on the third-order moments.

In uniformly sheared straight flows, the sign of shear makes no difference in producing the turbulence kinetic energy (Ahmad et al. 1976). However, when the shear flow is associated with streamline curvature, depending on the relative directions between the shear and curvature, the turbulence is either enhanced or suppressed. Therefore a quantitative understanding about the interaction between mean shear and curvature is crucial to the analysis of the complex turbulent flow field with streamline curvature.

Recently, an attempt has been made by Holloway and Tavoularis (1992, hereinafter referred to as HT) in which the effect of curvature on uniformly sheared turbulence was experimentally investigated in isolation from any other interacting mechanism such as the entrainment of irrotational flow, the proximity of viscous wall layers and the non-uniformity of the mean shear. A homogeneous shear flow for studying the interaction of pure shear and curvature was realized in a curved duct of which the cross section is 250 x 457 mm and the centerline radius \(R\) of 2.0 m and 5.0 m. The shear rate \(dU/\partial y\), was varied with a shear generator in a range, \(-64\leq dU/\partial y\leq 65\), and the curvature parameter \(S\) between \(-0.5\) and 0.64, where \(S\) is defined as the ratio of the curvature strain to the straight mean strain, \(S=(U/\partial R)/(\partial U/\partial y)\). Before discussing the experimental results, they analyzed the nondimensional equations describing the temporal evolution of the Reynolds normal and shear stress under the 'homogeneous shear' condition. They asserted that all dimensionless turbulence statistics in a curved homogeneous shear flow would depend on two parameters: namely, the dimensionless time \(\tau=(xU)\partial dU/\partial y\) and \(S\).

When \(S<0\), the curvature would enhance the production of turbulent kinetic energy and the Reynolds shear stress by the mean shear whereas the curvature opposes it when \(S>0\). The critical value of \(S\) for the onset of such opposite effects turned out to be 0.05 in their experimental result.

Although there have appeared a vast number of investigations in the past, quantitative information about the extent of curvature effects on turbulence structure is still lacking. The present experiment has been carried out to acquire quantitative information about the effects of interaction between the shear and the streamline curvature on the evolution of turbulence by investigating the turbulent flow field in a nearly two-dimensional 90° curved duct with a uniform shear inlet.

The present paper consists of four parts. The description of the experiment is given in Sect. 2. The Sect. 3 presents the wall static pressure and mean velocity profile. Turbulence structures in the curved duct under different shear conditions are discussed in Sect. 4. Parametric studies have been made to scrutinize the downstream evolution of turbulence under the curvature influence, which is described in the final part of Sect. 4.

2 Experimental apparatus and procedure

2.1 Wind tunnel and shear generator

Figure 1 shows a schematic layout of the present experimental apparatus. Air from a 7.5 hp centrifugal blower passed through a diffuser, a settling chamber and a two-dimensional contraction of area ratio 3.2:1. An adjustable shear generator was equipped at the exit of the contraction to provide a uniform shear flow at any desired shear rate. The basic design concept is similar to that of Chung and Kyong (1989). It consisted of nine equally-spaced channels, of which width was 19 mm. The flow passing through each channel was individually controlled by adjusting the opening of a damper which was composed of two parallel perforated acrylic bands with equally-spaced rectangular holes. The opening area ratio of the damper can be adjusted by sliding the one perforated band over the other in a range of 31.7% to 68.8%. The maximum mean shear rate, \(|dU/\partial y|\), obtained by the shear