# Experimental Investigation of a Swirling, Axisymmetric, Turbulent Boundary Layer with Pressure Gradient

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## Abstract

An experimental investigation of a swirling, axisymmetric, incompressible, turbulent boundary layer in an axial pressure gradient was carried out. The surface-flow measurements were accomplished with static-pressure taps and a miniature, directional surface-fence gage and were supplemented by oil-flow visualization studies. The data indicate that the streamwise pressure gradient controls the development of the streamwise component of skin friction but leaves the peripheral component unaffected. Calculations using a Reynolds-stress-equation turbulence model and a slightly modified experimental pressure distribution predict the attached flowfield and the location of the separation reasonably well.

## Contents

Several investigations of three-dimensional flows have been reported in the literature. A major program of study related to three-dimensional flows has been underway at NASA Ames Research Center with a view to improve the general understanding of three-dimensional viscous flowfields of practical interest and to assess/improve the applicability of existing turbulence models. In particular, Higuchi and Rubesin[1] studied swirling boundary layers by making mean-flow measurements in the relaxing flow region downstream of a spinning cylindrical section. Recently, Driver and Hebbar[2] continued the investigation of swirling boundary layers. In addition to surface-flow measurements, detailed measurements of mean and turbulence quantities were accomplished with a three-component laser Doppler velocimeter. The main conclusion of these studies was that the Reynolds-stress modeling seemed to have advantages over the eddy-viscosity models, and predictions based on it showed better agreement with the experimental data. The question remains whether the same conclusion holds under pressure gradient conditions; the present investigation[3] addresses this question. In particular, it is intended to study the effect of an axial pressure gradient on the transverse strain flow in the relaxing boundary layer.

### Experimental Setup

The experimental setup, described in Ref. 3, is essentially the same as that used by Higuchi and Rubesin.[1] Briefly, the experiments were carried out in a 305 mm × 305 mm low-speed, indraft wind tunnel, which has a 140-mm-diam circular cylinder mounted along its centerline (Fig. 1). A section of the cylinder can be rotated to produce a swirling boundary layer. The pressure gradient can be introduced into the flowfield by mounting a circular sleeve of suitable thickness on the stationary cylinder to act as a forward-facing step. Based on a series of static pressure measurements and oil-flow visualization studies with different step heights and locations, a 25.4-mm step located on the stationary cylinder at 154 mm downstream of the end of the spinner was selected as an optimum choice for the flow configuration.[3] This step height is comparable to the approaching boundary-layer thickness. The step location is such that the step-induced pressure field is practically zero at the trailing edge of the spinner. All the measurements were made at a nominal upstream Reynolds number of $2.4 \times 10^6$/m (corresponding to an upstream velocity of 36–37 m/s) with the rotation of the spinner set to make its peripheral speed equal the reference velocity.

Measurements reported herein include mean surface shear stresses (magnitude and direction) obtained using a two-element, miniature, directional surface-fence gage (overall diameter = 3.2 mm). The constructional and operational features of the miniature fence gage and its suitability for measurements in skewed flows under present conditions are discussed in Refs. 1, 3, and 4.

### Analysis of Data

Figure 2 presents skin-friction coefficients determined by the surface-fence gage with and without step and rotation. The overall accuracy of the data is estimated to be ±10%. It is clear that spinning increases the streamwise skin-friction coefficient $C_{fx}$ except in the vicinity of separation. In other words, spinning may be considered to increase the effective eddy viscosity of the fluid. With the step on the stationary cylinder, the flow behind the spinner is subject to a step-induced, streamwise, adverse pressure gradient. A preliminary evaluation and comparison of laser Doppler velocimeter data on mean and fluctuating velocity profiles with and without pressure gradient has confirmed a strong retarding influence of the pressure gradient primarily on the axial flowfield. The effect of the streamwise adverse pressure gradient is also clearly reflected in Fig. 2 in the development of streamwise skin-friction coefficient. It is reduced as the step is approached and goes through zero (the separation point) and reverses its sign close to the step. On the other hand, the

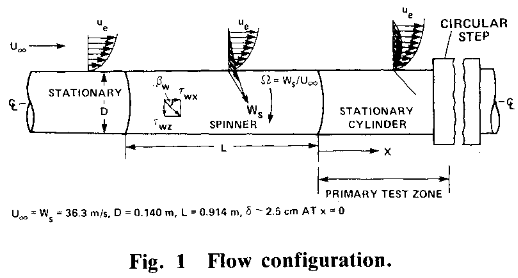


Fig. 1 Flow configuration.

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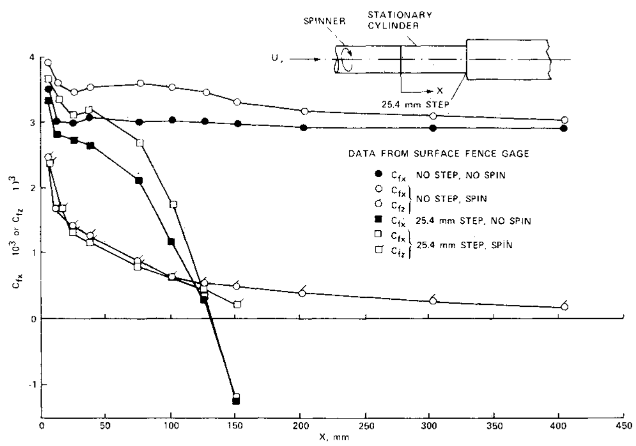


Fig. 2 Skin friction on stationary cylinder without step and with 25.4-mm step located at $x = 154$ mm from spinner.

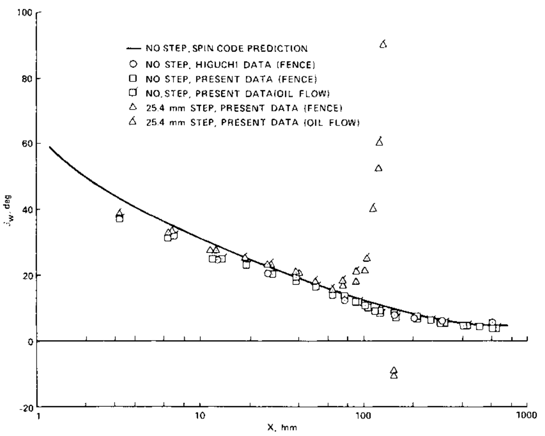


Fig. 3 Surface flow direction on stationary cylinder without step and with 25.4-mm step located at $x = 154$ mm from spinner.

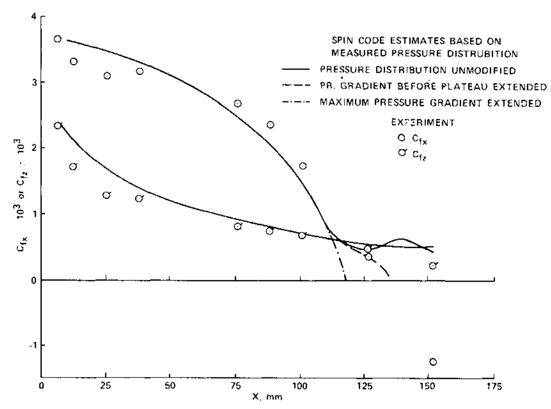


Fig. 4 Comparison between experimental data and spin code estimates of skin frictions based on measured pressure distribution with 25.4-mm step located at $x = 154$ mm from spinner.

peripheral skin-friction coefficient $C_{fz}$ remains practically unaffected by the pressure gradient until separtion is approached. The separation point is estimated to be at $x = 133$ mm or 19 mm ahead of the step. The separation bubble is therefore a short one, being only 19 mm long (about 3/4 step height).

Figure 3 presents surface-flow direction $\beta_w = \tan^{-1}(C_{fx} \div C_{fz})$, determined by the surface-fence gage to an accuracy of $\pm 1$ deg. Also included for comparison are Higuchi's fence data[1] and the present oil-flow data. The solid line represents the prediction of a boundary-layer code, which is discussed below. It is seen that the agreement among the various data sets is very good, particularly for the flow without the step. In the presence of the step, there is more turning of the flow as it approaches the step. This is caused by the fact that the pressure gradient continuously reduces the streamwise skin friction but leaves the peripheral skin friction practically unaffected. In fact, at $x \approx 133$ mm, the surface flow direction is nearly 90 deg, implying that the streamwise component is zero (compare Fig. 2). Further downstream, the direction of this component is reversed.

### Comparison with Computations

Computations were performed using an available boundary-layer code referred to here as "spin code." It is basically an implicit, parabolic marching method that uses a finite-difference scheme and is capable of handling different turbulence models. Earlier comparisons of the spin-code estimates with the experimental data for the relaxing boundary layer on the stationary cylinder (without step)[1,2] have yielded better agreement of the data with the code prediction based on the full Reynolds-stress equation for turbulence. It is shown here that, with the right choice of the impressed pressure field as input to the code, the development of the attached boundary layer and the location of the separation may be predicted reasonably well (see Ref. 3 for details). Figure 4 compares the distribution of streamwise and peripheral skin-friction coefficients. As expected, over most of the attached flow region, the three predictions hardly differ from one another (because the pressure field in unchanged), and they are in reasonable agreement with the experimental data. However, as the separation point is approached, they differ widely. The location of the separtion appears to be very sensitive to and largely dependent on the type of pressure distribution impressed through the separated region. The two predictions, based on extrapolated pressure distributions, yield results that are closer to the measured data. In the case of the peripheral skin-friction coefficient, all three predictions appear to fare well up to the separation point, thus suggesting that the peripheral skin friction is insensitive to the type of axial pressure distribution.

### Conclusions

Based on the analysis of the data and its comparison with the spin-code prediction, the main conclusions of this paper are:

1) Spinning has the effect of increasing the effective eddy viscosity of the fluid.

2) The streamwise pressure gradient primarily influences the streamwise component of skin friction, leaving the peripheral component relatively unaffected.

3) With extrapolated pressure distribution as input, the spin code, based on the full Reynolds-stress-equation turbulence model, predicts the attached flowfield and the location of the separation reasonably well.

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## References

[1]Higuchi, H. and Rubesin, M. W., "An Experimental and Computational Investigation of the Transport of Reynolds Stress in an Axisymmetric Swirling Boundary Layer," AIAA Paper 81-0416, Jan. 1981.

[2]Driver, D. M. and Hebbar, S. K., "Experimental Study of a 3-D Shear-Driven Turbulent Boundary Layer Using a 3-D LDV," AIAA Paper 85-1610, July 1985.

[3]Hebbar, S. K. and Driver, D. M., "An Experimental Investigation of a Swirling, Axisymmetric, Turbulent, Boundary Layer with Pressure Gradient," AIAA Paper 85-1668, July 1985; also, NASA TM 86768, Aug. 1985.

[4]Higuchi, H., "A Miniature, Directional Surface-Fence Gage," *AIAA Journal*, Vol. 23, Aug. 1985, pp. 1195–1196.