Effects of Compressibility on Boundary-Layer Turbulence

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Theme

A SET of detailed measurements of the turbulent flowfield in a subsonic, compressible, turbulent boundary-layer flow in the Mach number range of 0.1 to 0.7 is described. Profiles of quantities such as the turbulence intensities, the Reynolds shear stress, and the turbulent kinetic energy are obtained through the boundary layer. These measurements show that the lateral velocity fluctuations, and consequently the turbulent kinetic energy, exhibit a dependence on Mach number. It is also shown that turbulence models commonly used in numerical codes for the calculation of compressible flows will be affected by these results.

Contents

A recent review[1] of turbulence measurements in compressible flows indicates that only a very limited amount of experimental data exist in the subsonic and transonic regime. Since flows in this class are of great practical interest, there is a need to document them and to provide information on the turbulent fluctuations and shear stresses that would aid in determining the importance of compressibility effects.

A series of turbulence measurements were obtained[2] over a Mach number range of 0.1 to 0.7, including detailed surveys of the turbulence intensities, the Reynolds shear stress, and the turbulent kinetic energy. Comparisons with established experiments in the incompressible domain, such as those of Klebanoff,[3] were used to examine the effects of compressibility.

The experiments were conducted in a channel of rectangular cross section, 15 cm by 10 cm. Detailed boundary-layer surveys of both mean and fluctuating quantities were made about 3 m from the inlet, where the boundary layer was 3 cm to 4 cm thick. The mean-flow results are presented in Ref. 2. The turbulence measurements were made with hot-wire and hot-film probes in conjunction with DISA 55M constant-temperature anemometers, with a frequency response up to 80 kHz. In order to ensure that the velocity fluctuation data were not contaminated by total temperature fluctuations, tests were conducted using the mode diagram technique to establish the sensor response to mass flux and total temperature fluctuations.[2] The intensity of the temperature fluctuations was found to be negligibly small (less than 0.1%), and the sensor responded solely to mass flux fluctuations at the higher overheats at which the data were recorded. The determination of the effective sensitivity of yawed sensors is hampered by the fact that gradients in mean velocity and changes in fluctuations across the sensors introduce errors. To overcome this problem, only the velocity fluctuation ratios $\overline{v'^2}/\overline{(\rho u)'^2}$ $\overline{w'^2}/\overline{(\rho u)'^2}$, and the corresponding correlation coefficients $R_{(\rho u)'v'}$ and $R_{(\rho u)'w'}$ were obtained using yawed sensors. The streamwise fluctuations $\overline{(\rho u)'^2}$ were independently measured with single sensors not subject to these errors; and the shear and other fluctuations were then deduced from these measurements. Probe calibrations were free of drift and measurements of the velocity fluctuations and the turbulent shear stress were repeatable to within 10% and 15%, respectively.

Figure 1 shows the variation of the streamwise velocity fluctuations, u', through the boundary layer at various Mach numbers. Also plotted are the incompressible flat-plate boundary-layer measurements of Klebanoff[3] and Zoric.[4] The intensity of the streamwise fluctuations at the different Mach numbers varies from around 1% at the outer edge of the boundary layer to a peak of around 13% close to the wall. The data are shown here normalized by τ_w, the wall shear stress, and $\bar{\rho}$, the local mean density. Such a scaling was first suggested by Morkovin[5] to account for compressibility effects. The present data collapse on one curve, when plotted in this fashion, and show excellent agreement with incompressible results. The supersonic and hypersonic data of other experimenters also conform to this scaling, at least in the outer part of the boundary layer.[1]

This universality of the u' fluctuations suggests that the mechanism of turbulence production is not affected by compressibility effects such as temperature and density fluctuations.

The transverse velocity fluctuations v' also compare very well with the incompressible data over the present Mach number range.

The lateral velocity fluctuations w' depart from this trend. Unlike the u' and v' fluctuations, a systematic increase in magnitude results with increasing Mach number, especially in the inner half of the boundary layer. As shown in Fig. 2, this

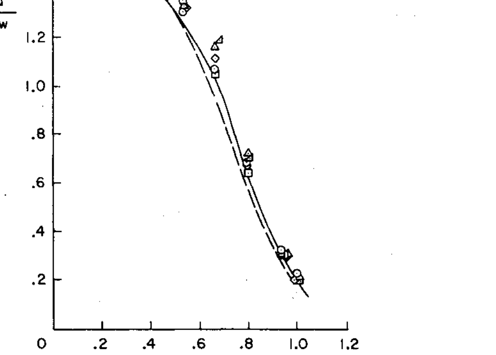

Fig. 1 Distribution of streamwise velocity fluctuations u' across the boundary layer.

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Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Subsonic and Transonic Flow.

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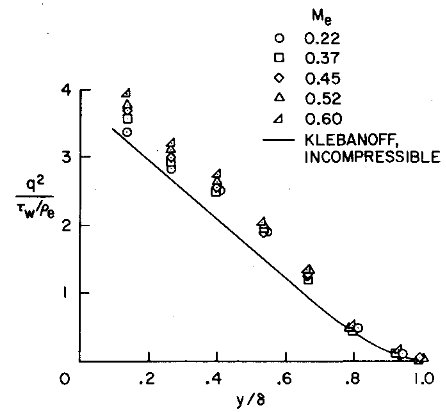

Fig. 2 Turbulent kinetic energy distribution across the boundary layer.

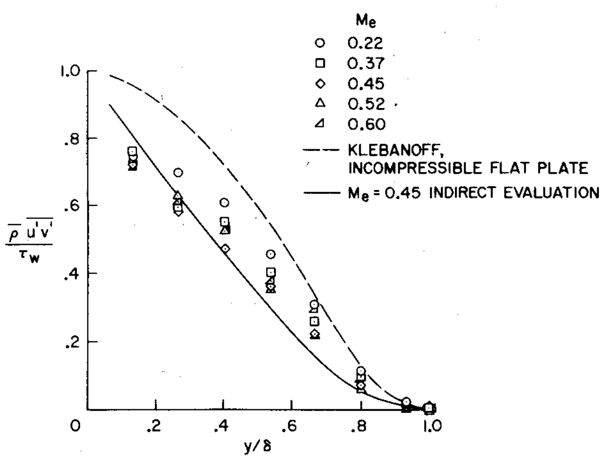

Fig. 3 Turbulent shear stress distribution across the boundary layer.

results in a corresponding increase in the turbulent kinetic energy $q^2 \equiv (\frac{1}{2})(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$, with Mach number. It should be noted that these measurements were made in the entrance section of a channel, where secondary flows are present. Since it is possible that the observed changes in w' with Mach number could in part be due to the three-dimensional nature of these secondary flows, extension of this result to turbulent boundary layers in general should be made with care.

Figure 3 presents profiles of the Reynolds shear stress $\bar{\rho}\,\overline{u'v'}$ normalized by the wall shear stress, at the various Mach numbers. The data scale well within the uncertainty of measurement, indicating that no Mach number effects are present. The data also follow the trend of the incompressible results but are lower, due to the slight favorable pressure gradient in the present experiment.

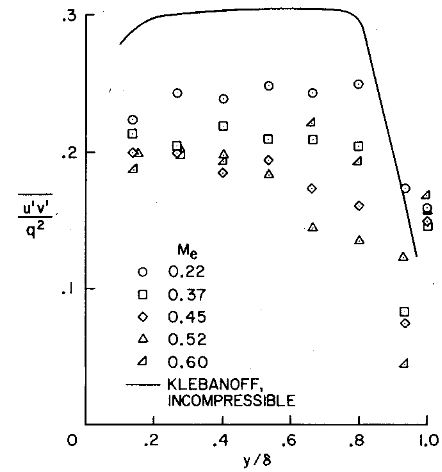

Fig. 4 Ratio of shear stress to kinetic energy.

The shear stress was evaluated indirectly by integrating the mean momentum equations, using experimentally determined value for the mean field parameters. The result for $M_e = 0.45$ shown in Fig. 3 is typical of the good agreement with experiment obtained using this technique.

In developing computer codes for the numerical simulation of turbulent flows, the crucial problem is usually the search for an appropriate turbulence model. Experiments such as this are valuable in providing guidelines for the generation of new and improved models, or insight into the physics of the problem.

As an example, when using a turbulent kinetic energy model, it is necessary to relate the turbulent correlation $\overline{u'v'}$ to the kinetic energy. The ratio of the two quantities is commonly assumed to be constant over most of the boundary layer for incompressible flows; Klebanoff's measurements bear this out. In the present experiment, however, the ratio was not constant but varied with Mach number, as shown in Fig. 4. It is possible that some models for compressible flows introduce errors into the computation by using a constant value for the ratio, based on the incompressible results.

References

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