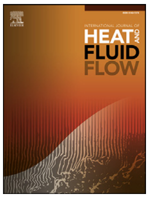
International Journal of Heat and Fluid Flow 68 (2017) 13–30

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff



Changes in flat plate wake characteristics obtained with decreasing plate thickness

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A R T I C L E   I N F O

Article history:
Received 8 February 2017
Revised 6 September 2017
Accepted 9 September 2017

Keywords:
Turbulent separating boundary layers
Shedding wakes
DNS
Effect of θ/D

A B S T R A C T

The near and very near wake of a flat plate with a circular trailing edge is investigated with data from direct numerical simulations. Computations were performed for four different Reynolds numbers based on plate thickness (D) and at constant plate length. The value of θ/D varies by a factor of approximately 20 in the computations (θ being the boundary layer momentum thickness at the trailing edge). The separating boundary layers are turbulent in all the cases. One objective of the study is to understand the changes in wake characteristics with changing θ/D (as obtained by decreasing D). Vortex shedding is vigorous in the low θ/D cases with a substantial decrease in shedding intensity in the largest θ/D case (for all practical purposes shedding becomes almost intermittent). Other characteristics that are significantly altered with increasing θ/D are the roll-up of the detached shear layers and the magnitude of fluctuations in shedding period. These effects are explored in depth. The effects of changing θ/D on the distributions of the time-averaged, near-wake velocity statistics are discussed.

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1. Introduction

The wake of the thin flat plate with a sharp trailing edge and turbulent boundary layers has been discussed in several articles, one of the earliest being that of Chevray and Kovasznay (1969). The ratio of the boundary layer momentum thickness to the trailing edge thickness of the plate (θ/D) is large (23.2) in their study. Profiles of measured mean velocity and turbulent normal intensities and shear stress are provided. The boundary layers merge gradually to form the wake. Large-scale vortex shedding is absent.

Ramaprian et al. (1982), based on their own experimental data for a flat plate with a sharp trailing edge, and data from other studies, conclude that the wake only reaches an asymptotic state for $x/\theta > 350$ (θ is the momentum thickness of the *wake* in their study); they refer to the wake region upstream of this location as the "developing wake". They suggest that the developing region be divided into the near wake ($x/\theta < 25$) and the intermediate wake ($25 < x/\theta < 350$). The near wake experiences the development of an inner wake and is influenced by the wall-layer of the upstream boundary layers. In the intermediate wake the effect of the upstream boundary layer diminishes and ultimately becomes insignificant.

Nakayama and Liu (1990) investigate the Reynolds number dependence of the wake centerline velocity profiles (normalized by the wall variables at the trailing edge), indicated by earlier experimental data. Their experiments (low Reynolds number, sharp trailing edge) show that indeed the profiles are Reynolds number dependent. They suggest that this is because of the effect of outer-layer eddies on the spreading of the inner wake.

Hayakawa and Iida (1992) obtained flat plate wake data with a sharp trailing edge (0.2 mm) to better investigate the very near wake ($x^+ < 500$, here the streamwise distance x is normalized by the wall shear velocity and kinematic viscosity near the trailing edge). The centerline velocity profile (starting at the trailing edge with increasing x^+, u^+ as a function of x^+, velocity normalized by trailing edge wall shear velocity) was found to be similar to the velocity profile of the zero-pressure-gradient turbulent boundary layer (with counterparts to the viscous sub-layer, buffer layer and the log-law). The peak values in normal intensity and shear stress profiles in the cross-stream direction were found to first increase in the streamwise direction (x), from that obtained at the trailing edge, before diminishing further downstream. Based on space-time correlations, the authors attribute the initial increase in intensities and shear stress to an interaction between wall turbulence from either side of the plate upon merger at the trailing edge and a change in orientation of longitudinal vortices. Of interest is a broadband peak obtained in centerline cross-stream velocity spectra, indicating quasi-periodicity (possibly due to vortices or wave-like motions).

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.09.003
0142-727X/Published by Elsevier Inc.

In addition to the experimental investigations mentioned above analytical solutions based on certain simplifying assumptions are provided by Alber (1980). In essence, the centerline velocity distribution in the x direction in a region of the near wake can be approximated by a logarithmic relation similar in form to that obtained for the turbulent boundary layer upstream of the wake in these cases. A good comparison is obtained between experimental data and the wake 'log-law' in the near wake.

Thomas and Liu (2004) report on an experimental investigation of symmetric and asymmetric turbulent wakes behind a flat plate. The thickness of the plate is tapered down to 1.6 mm in the last 0.2 m of the plate length. Hence, as in earlier flat plate wake experiments, little or no vortex shedding is expected. The asymmetric wake is obtained by introducing a semicircular bump on the lower side and a suction slot on the upper side. The net effect is a ratio of θ_L/θ_U of 2.5. Data are provided for adverse, favorable and zero pressure-gradient wakes.

In contrast to the thin plate with a sharp trailing edge, the thick plate with a blunt trailing edge (small θ/D cases), exhibits vigorous vortex shedding. Unlike the case of the cylinder, the Reynolds number based on momentum thickness of the boundary layer just upstream of the trailing edge (Re_θ) and the Reynolds number defined using the thickness of the flat plate or the diameter of its trailing edge (Re_D), are independent parameters. A detailed investigation of the wake of the thick plate with a circular trailing edge and, *turbulent separating boundary layers,* was initiated by Rai (2013, 2014, 2015). This was accomplished with the aid of direct numerical simulations (DNS). The boundary layers as well as the wake were computed via DNS in these investigations. The separating boundary layers are fully turbulent well upstream of the trailing edge and are statistically identical. Thus the wake is symmetric in the mean.

In Rai (2013) distributions of the phase-averaged turbulent intensity and shear stress (random component) in the near wake are explored and compared with cylinder experimental data. Wherever possible a physical explanation of the origin of the important features of the distributions, as well as one based on the distribution of the production term in the corresponding budget, is provided. A new event- based phase-averaging procedure is introduced. Some of the important features of the near wake, such as the structure of rib vortices and their strength (in relation to the shed vortices), their evolution in time, the internal structure of shed vortices etc. are explored here. Some of the findings are as expected (rib vortices in the braids) while others such as the presence of intense elongated spanwise vortices instead of a single columnar vortex in the cores provide new understanding of the cores and braids and the interaction between them. Earlier research had primarily dealt with rib vortices as they occur in the braid and the amplification of the streamwise and transverse vorticity associated with them by vortex stretching as a result of the associated strain rate. In Rai (2013), it is found, that on average the stretching of rib vortices via the phase-averaged strain rate produces significantly less turbulent vorticity than that produced by turbulent stretching both in the braids and in the cores. In particular the data show the importance of turbulent stretching in sustaining fluctuations in the spanwise component of vorticity.

In Rai (2014) the emphasis is on the stability of the detached shear layers, rib-vortex induced reverse flow, and phase-averaged distributions of the random component of normal intensities and shear stress and the production term in the corresponding budgets in the *very* near wake ($x/D<3.0$). It was determined that, as in the case of the cylinder with laminar separating boundary layers, the flat plate wake also exhibits shear layer instability followed by the formation of shear layer vortices that have a profound impact on the structure of the shear layer and the formation of the shed vortices. However, unlike the cylinder cases, here only a small fraction of the separated turbulent boundary layer participates in the initial formation of the shed vortices and, it is this fraction that is unstable. As in Rai (2010) (cylinder case), periods of shear layer instability correlated well with the interaction of the shear layer with recirculation region vortices, and quiescent periods showed little or no interaction between the two. This is a strong indicator that this interaction is an important contributor to initiation of the instability. Spectra of the time-varying velocity and pressure within the shear layers at $x/D=0.5$ were obtained. Unlike the cylinder case with laminar separating boundary layers, the spectrum of streamwise velocity did not show a broadband peak. This is because of the large velocity fluctuations that are already present in the detached shear layer at its inception (turbulent separating boundary layer). The pressure signal on the other hand showed a clear broadband peak with the characteristic shear layer frequency.

An examination of the distribution of streamwise velocity in the wake center-plane (Rai, 2014) first led to the discovery of regions of isolated reverse flow that are disconnected from the main body of reverse flow in the trailing edge region. They are first formed near the trailing edge and convect downstream. These regions are a result of powerful rib vortices that are formed in the high-strain-rate region that exists between the shed vortices in their initial state; they are quite energetic with streamwise velocities (negative) within them reaching 40% of the freestream velocity. They are accompanied by pressure minima and relatively high cross-stream vorticity levels and are observed as far downstream as $x/D=4.0$. These reverse flow regions occur at multiple spanwise (z) locations within short periods (25% of shedding period); thus they appear along nearly constant time lines in a (t, z) plane at a given x location in the wake center-plane. Two such lines of reverse flow (each line corresponding to the passage of a shed vortex) are observed per shedding period. A spectral analysis of the z-averaged negative streamwise velocity shows a peak at twice the shedding frequency thus confirming the frequency of occurrence of these lines of multiple reverse flow regions. The passage of the shed vortices over a given x location reduces the local streamwise velocity near the center-plane thus creating favorable conditions for rib-vortex induced reverse flow. Since all such regions of isolated reverse flow investigated showed an associated rib vortex, it was concluded that the rib vortices were the causative agent. These regions eventually weaken and disappear; probable reasons being a re-orientation of the rib vortices (lowering of cross-stream vorticity) and the increase in streamwise velocity with increasing x.

In Rai (2015) the emphasis is on entrainment and the instability of the detached shear layers. As mentioned earlier only a small fraction of the separating turbulent boundary layer forms the detached shear layer and participates in the initial roll-up into the shed vortex. A natural consequence of this behavior is that for some distance downstream the wake with its shed vortices ingests fluid that was originally part of the turbulent boundary layer. The log-layer eddies are assimilated in this process and become a part of the shed vortices or the braids; a visualization is provided in the article. An investigation of the effect of increasing θ/D on assimilation/entrainment is also provided. It clearly shows that wakes with larger θ/D values continue to assimilate boundary layer fluid for longer (until a larger value of x/D); the important contributors to this effect are identified. The study also shows that wake TKE profiles, in the region away from the shed vortices and braids, are close to that of the upstream turbulent boundary layer (especially in the very near wake for the large θ/D cases). This again is a consequence of the fact that much of the turbulent boundary layer does not participate in the initial shed-vortex roll-up process.

A visualization of shear-layer instability events in a (t, z) plane in Rai (2015) showed that shear-layer vortex generation rates can vary as much as a factor of two from event to event. An analysis of velocity fluctuations in the upstream boundary layer indicated that