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The work under this grant has consisted of a fairly broadly aimed theoretical analysis along several fronts with the aim of understanding the basic mechanisms responsible for the creation of turbulence in a boundary layer and the possible use of this knowledge to explain observed phenomena of turbulent drag reduction through polymer addition, etc,, as well as to be able to propose new and improved drag reducing methods. The work has progressed along three main lines of attack which are: (A) Theoretical modeling of boundary-layer turbulence, (B) Mechanisms involved in laminar-turbulent transition in a boundary layer and (C) Drag reduction mechanisms.

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INTRODUCTION

The work under this Grant has consisted of a fairly broadly aimed theoretical analysis along several fronts with the aim of understanding the basic mechanisms responsible for the creation of turbulence in a boundary layer and the possible use of this knowledge to explain observed phenomena of turbulent drag reduction through polymer addition, etc., as well as to be able to propose new and improved drag reducing methods. The work has progressed along three main lines of attack and is continued under a followup AFOSR Grant. The three main lines are:

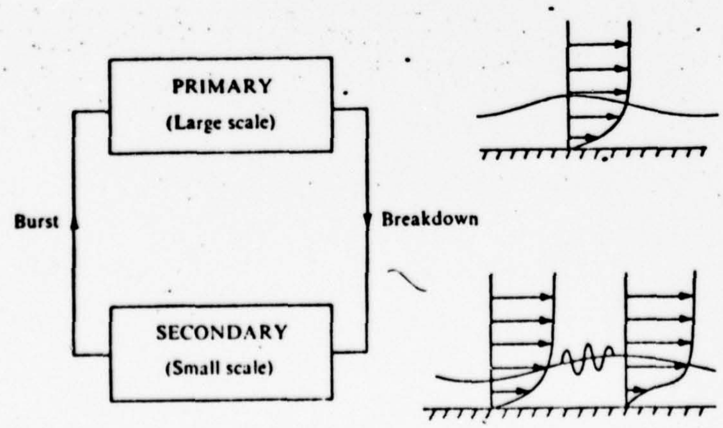
A. Theoretical modeling of boundary-layer turbulence

B. Mechanisms involved in laminar-turbulent transition in a boundary layer.

C. Drag reduction mechanisms

A. Modeling of boundary layer turbulence

The fundamental basis for this work has been the conceptual two-scale model for boundary layer turbulence proposed under earlier AFOSR-sponsored contracts and grants (Landahl, 1973, 1975). The fundamental ideas of this model are illustrated by the figure below (from Landahl, 1975)



This model, which is quite unconventional in that it postulates both a forward cascade of eddies (i.e., large eddies produce smaller eddies, and so on, the "classical" cascade) and a reverse cascade (small-scale eddies regenerate large-scale ones), has required no essential revisions during the subsequent developments, which has been devoted to investigate the various detailed generation and interaction mechanisms proposed in the model.

Earlier developments preceding the formal two-scale model proposal (Landahl, 1967) had demonstrated that long-time statistical averages of the fluctuation field such as the cross-power spectral density of the pressure fluctuations would be dominated by wavelike components, which would presumably contribute primarily to the large-scale component. Landahl's (1967) wave-guide model was first applied to explain the statistical properties of pressure fluctuations; reasonably good agreement was found between the measured convection velocity and decay rate and the theoretical prediction mode on the basis of the Orr-Sommerfeld equation using the mean turbulent profile. Evidence for waves in the viscous sublayer were later presented by Morrison & Kronauer (1969); Bark (1975) showed analytically that the wave-guide model gave good prediction of convection velocities and decay rates observed and also could give a good estimate of the location of the peak wave-number-frequency spectrum for the velocity fluctuations in wave-number space. Recent observations by Hofbauer (1978) of turbulent channel flow has given direct visual evidence for the presence of damped waves in the sublayer, thus vindicating the wave-guide idea.

However, from later work (Landahl 1975, 1977a) it has become clear that only the v-velocity component (normal to the wall) and the pressure fluctuations would show a clear wave behavior; for the other two fluctuating velocity components there will also arise convected and transient portions not showing wave-like behavior, which may dominate these components. An analysis of a large-scale coherent structure during the last grant period (Landahl, 1978a), which was based on the assumption of a large horizontal scale of the disturbed region and neglect of viscosity, shows a space-time development of the structure in good qualitative agreement with the conditionally sampled data of Blackwelder and Kaplan (1976), and also with the instantaneous streamwise velocity perturbation profiles of Zakkay et al (1978). The approximate analysis also allows nonlinear effects to be incorporated (Russell 1978). The most significant of the theoretical findings is the demonstration that a large-scale eddy induced by a local production of turbulent stress tends to develop with time into a thin internal shear layer with a shear strength limited only by viscous diffusion. One of the most distinguishable properties of the structure of turbulence in the wall region observed in practically all recent experimental studies is indeed the presence of thin internal shear layers, an observation that was universally agreed upon at the 1978 Lehigh Workshop (report by Committee 3, Smith & Abbott, 1978). The thin shear layers will be inflexionally unstable and thus may precipitate another breakdown into small-scale motion, with a subsequent burst. Hence, the theoretical consistency of one of the proposed interaction links in the model, that between the large-scale and small-scale eddies, has been confirmed.

In the two-scale model, the large-scale motion (the coherent eddy) is assumed to be initiated by the collective action of the small-scale motion. This idea has been given some experimental support by the observations of Smith (1978). It was demonstrated (Landahl 1975, 1977a, 1978a) that the eddy thus induced has a definite sense of rotation which is opposite to that of the mean shear, i.e., the moment of momentum induced by the mixing is such as to produce an upward motion, away from the wall, in the downstream portion of the eddy, and downward, towards the wall, in the upstream portions. Direct confirmation of this prediction may be found in the recent publication by Chen and Blackwelder (1978). It is interesting that the localized shear layer emerging as the large-scale disturbance evolves has a vorticity of the same sign as the mean vorticity (see Landahl, 1978a), the reason being that the shear layer is produced through the stretching of the mean vorticity by the disturbance.

A new method of analysis has been developed (Landahl, 1978a) for the evolution of a large-scale coherent structure having a large horizontal extent compared to the thickness of the wall layer. The assumption of a "pancake-like" region of disturbed flow allows the substantial simplifications of boundary-layer-type approximations to be made. Thus, for example, the pressure may be taken as independent of the coordinate normal to the wall and equal to its value at the edge of the wall layer. Also, the horizontal pressure gradients are found to be comparatively weak, which makes feasible a Lagrangian (material) coordinate flow description leading to a new fairly general method for calculating the nonlinear evolution of a localized disturbance. In the first approximation the effects of pressure gradients may be neglected giving the answer in terms of a single line integral. It is shown that for a disturbance of large horizontal scale, pressure becomes important only for long times, when the disturbance has traveled downstream a distance of many times its own length. By taking pressure into account through an iterative process, a computational scheme which includes the effects of nonlinearity may be developed. Further work by Russell (1978) shows that integration of the vorticity equations in a Lagrangian frame may be a particularly efficient approach.

In the first approximation, in which effects of pressure, nonlinearity and viscosity are all neglected, the vertical displacement of each fluid element is given as a simple line integral involving the initial vertical disturbance velocity distribution. A preliminary analysis of the long-time effects of the pressure disturbances based on linear theory (Landahl, 1978a) shows that the pressure acts primarily through the spanwise gradient rather than through the streamwise one as has sometimes been proposed in the literature. Also, the pressure is instrumental in the generation of wave-like disturbances, which is particularly important in connection with the mechanism of transition through the nonlinear evolution of Tollmien-Schlichting waves. This aspect is discussed under B below.

A fundamental question in a dynamical model of the kind explored is whether it is consistent from an energy point of view. This question has not been addressed so far because the concern has been primarily with inviscid mechanisms in order to try to explain the rapid interaction mechanisms which are observed during turbulent bursting. To analyze the overall energy budget one would have to include long-time effects such as those due to viscosity, as well. However, one immediate question that is raised by the two-scale model is whether the large-scale fluctuations, being initiated by the nonuniform mixing due to the small-scale breakdown, an effect proportional to the square of the small-scale amplitude and hence of small magnitude, are able to extract enough kinetic energy through interaction by the mean shear flow to produce through their breakdown small-scale fluctuations of sufficient amplitude to regenerate a new burst. A partial answer is provided by the discovery of a new inviscid instability mechanism (Landahl, 1978d) to be discussed further below, which shows that, for a certain broad class of three-dimensional initial infinitesimal perturbations on any inviscid parallel shear flow, the total energy of the disturbance will grow linearly with time, thus indicating that in a flow of low viscosity the basic mechanism drawing kinetic energy from the mean shear may be an instability of an algebraic kind rather than of an exponential kind as in the case of a turbulent free shear layer.

In addition to the publications quoted, various aspects of the boundary-layer-turbulence-modeling problem have been discussed in invited lectures at international scientific meetings (Landahl, 1976a, 1977a, 1978b). Also, this work was included in a series of lectures on turbulence given as the Principal Lecturer at the Woods Hole Oceanographic Institution Geophysical Fluid Dynamics Program, Summer of 1977 (Landahl, 1977b) and in a series of seminars presented at Stanford University, summer of 1978, as well as in invited seminars at many of the leading universities.

B. Mechanisms involved in laminar-turbulent transition in a boundary layer

One of the main themes followed in the research under the present Grant and its predecessors has been the efforts to relate laminar-turbulent-boundary-layer transition phenomena to the mechanism of turbulence generation in a fully developed turbulent boundary layer. Grossly speaking, the turbulent bursting may be thought of as a local transition inside the turbulent boundary layer. What speaks for a strong qualitative similarity between bursting and transition is the intermittent onset of small-scale turbulence (see in the spike-formation stage of turbulence), the strong three-dimensionality in the unsteady flow field and the presence of a thin internal shear layer with strong shear just preceding the small-scale onset. Despite the large amount of work devoted to the transition problem during the hundred years since Rayleigh published his famous 1873 paper, there is still no universal agreement among fluid dynamicists about the nature of all the various mechanisms involved and their details. The wave-mechanical model of breakdown (Landahl, 1972) focussed on the phenomenon of rapid onset of small-scale oscillations and devised a simple criterion for breakdown based on the condition for the appearance of space-time focussing of small-scale secondary instability waves on the non-homogeneous flow field associated with large-scale (comparatively) Tollmien-Schlichting waves. This criterion, which states that breakdown should occur when the group velocity of the secondary instability becomes equal to the phase velocity of the primary (Tollmien-Schlichting) wave, was found to be in complete agreement with the measurements of Klebanoff et al (1962). Unfortunately, so far there have appeared no measurements on breakdown in the literature detailed enough to allow additional quantitative comparisons. Recent experimental investigations of transition have emphasized the behavior of a turbulent spot

(Cantwell et al 1978, Wygnanski et al 1976), in particular its spreading behavior. The experimental findings raise many theoretical questions concerning the relationship between the Tollmien-Schlichting waves and the evolution of the spot which may require a reassessment of the linearized wave theory. A treatment of the initial-value problem for an infinitesimal three-dimensional disturbance in a laminar boundary layer (Gustavsson, 1978) proceeds from a Fourier-Laplace transform of the problem in horizontal space and time. This gives as a result a nonhomogeneous Orr-Sommerfeld-type equation in which the initial velocity distribution of the disturbance appears as the non-homogeneous right-hand side of the equation. (It may be remarked that mathematically the equation has the same structure as that appearing in the 1967 Landahl wave-guide model, thus establishing a strong mathematical relationship of the initial-value problem to that for the fully developed turbulent boundary layer). By a formal solution of this equation, it is shown that the resulting disturbance velocity may be represented as a discrete spectrum of (Tollmien-Schlichting) waves plus a continuous spectrum portion convected downstream with the free-stream velocity during a slow viscous decay. The presence of the continuous spectral portion has been pointed out earlier, but Gustavsson's (1978) work is the first to show how this portion is related to the initial perturbation. The finding that the disturbance can spread with a downstream velocity equal to that of the free stream is of great importance for the understanding of the spreading velocity of a turbulent spot, the leading edge of which has been observed to propagate with a velocity of about 0.9 of the free-stream velocity. A discussion of the wave-mechanical aspects of transition-spot spreading (Gustavsson & Landahl, 1978) leads to the conclusion that the spot is a region of essentially fully developed turbulent boundary layer spreading into the laminar region by wave breakdown along the edges, primarily occurring along the "wing tips" of the spot region. The observed spanwise spreading rate is found to be consistent with this idea as well as the shape and instantaneous position of the swept leading edges of the spot.

Strong shear-flow instability has always been believed to be associated with velocity profiles with inflection points following Rayleigh's original finding that such a profile may show exponential growth of an infinite wave train of infinitessimal amplitude. The mean velocity profile in a turbulent boundary layer over a flat plate has a velocity profile curvature of one sign only and is therefore expected to be hydrodynamically stable, as calculations based on the full Orr-Sommerfeld equation (Landahl, 1967) also show. Thus, on this basis, one would therefore expect that finite-amplitude instability mechanisms are at work in causing bursting in a turbulent boundary layer. However, a dismissal of linear instability mechanisms as an important consideration requires one to study the behavior of all possible initial infinitesimal disturbances as they develop in the inviscid shear layer. By employing averaging of the equations of motion in the streamwise direction Landahl (1978d) was able to demonstrate in a very simple manner that the total momentum and the kinetic energy of a localized initial perturbation in any inviscid shear flow, whether possessing an inflection point or not, would grow linearly in time for a wide class of initial velocity distributions. The explanation is that it is not the disturbance amplitude which grows, but the streamwise length of the affected region. It is believed that this finding may be of substantial eventual importance for the understanding of transition and bursting phenomena. For example, it could provide an explanation for the prevalence of a longitudinally streaky structure found in the high-shear region near a wall in transitional and fully developed boundary layer flows. Viscous diffusion will limit this growth mechanism for large times, but the possibility of producing large perturbation energies from small localized three-dimensional disturbances in a shear flow of low viscosity certainly emerges from this study.

C. Drag reduction mechanisms

The observations that one may achieve large reductions in turbulent skin friction drag in fluid by the addition of certain polymers and other agents has stirred a great deal of interest in the Fluid Dynamics community, both because of possible engineering applications of such techniques and from the fundamental fluid dynamical point of view, since the drag reduction phenomenon could possibly reveal important information about the stress-producing mechanisms in the turbulent boundary layer (Landahl, 1973). For this reason, an international IUTAM Symposium on the Structure of Turbulence and the Mechanism of Drag Reduction was organized in 1976, partly at the instigation of the principal investigator. The proceedings of this meeting (Frenkiel et al, 1977) give a fairly comprehensive picture of the experimental and theoretical understanding of that field at that time. The main experimental finding of the effect of polymer drag reducing additives is that they cause an increase in the scales of motion in the viscous sublayer, thereby reducing the velocity gradient at the wall and hence the wall shear stress. The theoretical explanation due to Landahl (1977a), based on stability calculations, is that the extended polymer molecules, acting primarily as rigid rods aligned with the mean flow, cause a stabilization of the small-scale motion, thus interrupting the main stress-producing mechanism. Also other observed drag reduction phenomena could be explained qualitatively on basis of stabilization of local inflectional instability. However, stability investigations under way by Bark and Tinoco at the Royal Institute of Technology in Stockholm show that rigid rods may in fact cause a destabilizing of some three-dimensional waves (the calculations discussed in Landahl 1973 and 1977a were for two-dimensional disturbances) so this issue is not yet resolved. An alternative explanation suggested by the recent work on coherent structures is that the additives may inhibit spanwise vortex stretching thereby limiting the intensity of the shear in the internal shear layer formed during bursting. The increase in the thickness of the shear layers would thereby lead to an increase in the thickness of the viscous wall layer and a corresponding decrease in stress.

Summary of research accomplishments under the Grant

To summarize the research accomplishments under this Grant: We have been able to propose and develop a mechanistic boundary layer turbulence model which shows many of the properties observed in experiments on wall-layer turbulence structure. Many but not all of the proposed interaction mechanisms between small- and large-scale eddy motion have been verified by detailed theoretical analysis, such as the formation of thin shear layers by the large-scale motion and the overall sense of large-scale rotation induced on the flow by small-scale mixing. Still to be studied is, for example, the coupling mechanism between outer and inner flow responsible for the outer-parameter scaling of sublayer bursts.

Many of the ideas expressed in the two-scale model have direct application to transition processes, and this problem has therefore also been pursued along several lines. From the theoretical knowledge gained so far from this research program it appears there are two fundamental mechanisms in the turbulence generation cycle that it may be possible to interfere with so as to reduce turbulent drag, namely, the formation of thin shear layers in the viscous sublayer region and their breakdown into turbulence.

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