ME 38-89 (N)

Proposal for Research
AND
PROGRESS REPORT

EXPERIMENTAL INVESTIGATION OF THE
THREE-DIMENSIONAL BOUNDARY LAYER ON
A ROTATING DISK

Submitted to:
U.S. Department of Energy
Office of Basic Energy Sciences

by

John K. Eaton
Associate Professor
Department of Mechanical Engineering
Stanford University

January 1989

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ja

T4

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

EXPERIMENTAL INVESTIGATION OF THE THREE DIMENSIONAL BOUNDARY LAYER ON A ROTATING DISK

ABSTRACT

An experimental study of the velocity and temperature field above a heated spinning disk is proposed with relevance to general three-dimensional boundary layers and specific rotating disk problems. Disk tip Reynolds numbers will range from 100,000 to 1.6 million, the latter being in the fully turbulent regime. Measurements will include the surface heat transfer coefficient, the mean temperature field, the mean velocity field, all components of the Reynolds stress tensor, and higher order statistics with particular emphasis on the near wall region. The boundary layer structure will be examined using both quantitative measurements and flow visualization carried out in a parallel water flow facility.

1. INTRODUCTION

The design of energy conversion systems is often critically dependent on accurate estimates of convective heat transfer rates. Highly uncertain estimates of heat losses or thermal loading necessitate conservative designs which lead to lower system performance, and higher cost, weight, and complexity. Most heat transfer design for turbulent flow situations is done using empirical correlations developed in geometries which are either very simple or quite specific to a particular application. Accurate and general purpose heat transfer design requires advanced computational techniques to predict the fluid flow and temperature field for a wide range of system geometries.

The development of computational techniques for turbulent convective heat transfer requires at least three types of input from experiments. The first type is benchmark quality heat transfer data including an accurate specification of the boundary conditions and measurements of either the heat transfer coefficient or the temperature field. Such data sets are used to test the performance of computer codes for typical applications

but cannot be used to determine which part of the computational model is failing if the performance is poor. Type 2 experiments are those that supply detailed fluid flow and temperature field data allowing explicit comparison to models for various regions of the flow. For example, mean velocity, Reynolds stress, and dissipation rate measurements are needed to examine the behavior of standard 2-equation turbulence models. Type 3 experiments are designed to supply physical insight into the mechanisms governing the heat transfer rate and would generally include either flow visualization or multipoint measurements.

Benchmark quality heat transfer data (Type 1 experiments) are available in the archival literature and a number of laboratories continue to produce high quality measurements of this type. However, there is a shortage of Type 2 or 3 data, particularly for "complex" three dimensional flows. This is because of the difficulty in performing such experiments which generally require the use of several different complex measurement systems. For example, a Type 2 experiment requires the acquisition of both temperature and velocity field data and in most cases the measurement grid must be sufficiently dense to allow direct differentiation of the data.

The majority of experiments producing results of Types 2 and 3 above have been conducted in relatively simple two-dimensional or axisymmetric geometries. There is a large community of researchers devoted exclusively to understanding the detailed structure and mechanisms involved in thermal transport in two-dimensional boundary layers (2DBLs); over 50 papers on structure and modeling of 2DBLs were presented at the recent Zoran Zaric Memorial International Seminar on Near-Wall Turbulence [1] There have been detailed two-dimensional boundary-layer experiments in class 2 above including the effects of longitudinal curvature, freestream turbulence, separation and reattachment, favorable and adverse pressure gradient, surface roughness and other perturbations.

Unfortunately, the turbulence structure and heat transfer mechanisms in 2D boundary layers may not be representative of those found in three-dimensional boundary

layers (3DBL's) which are much more common in practice. A three-dimensional boundary layer is a wall-bounded shear flow in which components of the velocity both parallel and transverse to the freestream velocity are important as sketched in Figure 1. The simplest three dimensional boundary layers are those which are spanwise homogeneous, that is there are no significant gradients in the z -direction of Figure 1. Even such simple 3DBL's exhibit striking changes in the turbulence structure [2,3] including substantial reductions of the turbulence stresses.

A key feature of the 3DBL is that there is a significant longitudinal component of the mean vorticity which may either reduce stresses by rotating eddies out of preferred orientations as advocated by Bradshaw [2] or interfere with the turbulence producing instabilities normally active in a 2DBL as proposed by the present author [3]. The mean longitudinal vorticity is particularly strong in the near wall region and appears to have a significant impact on the structure of the logarithmic and viscous regions of the boundary layer. In a recent review, Launder [4] made a strong point that these lower layers of the boundary layer are critical in determining the heat transfer rate. It cannot be assumed *a priori* that models developed for 2DBLs can be satisfactorily generalized to 3DBLs. Fundamental experiments on three-dimensional boundary layers must be conducted to determine if widely accepted concepts and turbulence models are applicable in 3D flows.

A long-range program is underway at Stanford to examine the heat transfer behavior of 3DBL's. The first flows studied were 2D boundary layers with weak three dimensional disturbances, namely large scale longitudinal vortices [5,6]. Next, boundary layers perturbed by stronger vortices and pairs of vortices were examined [7,8,9]. The present experiments are focussing on a pressure-driven three dimensional boundary layer developing ahead of a wedge [3,10,11]. The first two experiments are complete and include spatially resolved measurements of the heat transfer coefficient and the skin friction coefficient coupled with detailed field measurements of the mean temperature, mean velocity, the full Reynolds stress tensor, and the dissipation rate. The data are sufficiently detailed to allow direct evaluation of the constants in turbulence models as

shown in reference 7. The mean velocity and Reynolds stress measurements are complete for the third experiment and we are presently acquiring the heat transfer data. In addition, a new laser anemometer concept to extend the velocity measurements into the sublayer is under development.

The experiments with stronger three dimensionality have shown major modifications of the turbulence structure and significant changes from 2D boundary layer heat transfer behavior. One of the biggest problems in analyzing these experiments is that they are inhomogeneous in the spanwise direction (as are most other 3DBL experiments). This proposal presents a plan for a new experiment to be conducted in the boundary layer on a single rotating disk. This flow was selected because it provides a strongly three dimensional boundary layer that only has two significant space dimensions. The flow is also directly relevant to problems in turbomachinery and other rotating machinery.

The overall objectives of the research program then will be to document both the heat transfer and fluid mechanical behavior of the single disk flow with particular emphasis on the impact of three dimensionality on the flow structure. Detailed objectives will be laid out following the Literature Review which sets the context of this work.

2. LITERATURE REVIEW

This section is split into three subsections. The first two review relevant work in three dimensional boundary layers and rotating disk flows. The body of literature in these fields can be clearly separated since the two communities have remained largely separate. The third section gives a brief summary of current knowledge of 2D boundary layer structure.

2.1 Fundamental Experiments on Three Dimensional Boundary Layers

Three-dimensional boundary layers may be divided into 3 types based on how the three dimensionality is generated. The most common 3DBLs are called "pressure-driven" because the boundary-layer skewing is caused by a spanwise pressure gradient. Typically, the pressure gradient is developed when the freestream is forced to turn around an obstacle. The low-speed flow near the wall turns more sharply producing

a skewed velocity profile. "Shear-driven" secondary flows develop when the flow is exposed to a wall moving in the spanwise direction such as in the rotating cylinder experiments by Driver and Hebbar [12]. Finally, secondary flows of the second kind are generated by gradients in the Reynolds stresses in flow configurations like streamwise corners. Generally, the crossflow velocities are small in the latter class of flows and are overwhelmed if any pressure-induced secondary motion is present. This review will concentrate on studies of pressure-driven flows which are most relevant to practical applications and the present work.

Early work in 3DBLs was primarily concerned with measuring the mean velocity profiles with the emphasis on providing information for boundary layer calculations using integral methods. Experiments through 1976 were reviewed by Johnston [13] who concluded that no single profile family could represent the entire range of mean velocity profiles observed to date. It was found that outer layer (wake) profiles could be computed using inviscid theory (Squire and Winter, [14]) if the boundary layer was initially 2D and was turned rapidly, but failed if the turning was applied more slowly because there was ample time for shear effects to diffuse away from the wall (c.f. Senoo and Nishi [15]). Pierce *et al.* [16,17] reviewed and tested 11 different similarity models used to describe the profile in the near-wall region. The models were basically extensions of the 2D logarithmic law of the wall. Most models performed well for y^+ values between 50 and 300 if the skew angle between the wall and the freestream was less than about 15° . However, the performance of the similarity models was poor for strongly skewed flows suggesting that the flow structure was significantly different than a 2DBL. Very few mean profile measurements extend into the viscous sublayer so the behavior of the velocity vector approaching the wall is not well known. Early work by Johnston [18] suggested the existence of a region of collateral or parallel flow near the wall, but subsequent work by Rogers and Head [19], Vermeulen [20], Prahlad [21], Klinksiek and Pierce [22], and others showed significant flow direction changes within the viscous sublayer.

In the late 1960's research in boundary layer prediction methods shifted emphasis from integral to differential methods requiring a more detailed understanding of the

boundary layer and a model of the turbulence. Experiments then focused on supplying single-point turbulence measurements appropriate for model testing. Anderson and Eaton [11] provided an extensive review of experiments which provided Reynolds stress measurements. The simplest such experiments are the “infinite swept wing” experiments performed by van den Berg *et al.* [23] and Bradshaw and Pontikos [2]. The shear stress vector (formed from the $\overline{u'v'}$ and $\overline{v'w'}$ components of the Reynolds stress tensor) was found to lag behind the rotation of the strain rate vector (formed from the $\partial U/\partial y$ and $\partial W/\partial y$ components of the strain rate tensor). Also, the ratio of the shear stress vector magnitude to the turbulent kinetic energy fell sharply.

The lag in the shear stress vector behind the strain rate was also observed by Johnston [24], East and Sawyer [25], Baskaran and Bradshaw [26,27], Dechow and Felsch [28] Anderson and Eaton [3], and Driver and Hebbar [12]. This seems to be a common feature of initially 2D boundary layers which are turned monotonically. On the other hand Ezekwe *et al.* [29], Fernholz and Vagt [30], and Muller [31] all observed a lead in the shear stress vector ahead of the strain rate. Fernholz and Vagt concluded that this was caused by rapid distortion of the turbulence. Van den Berg [32] observed that this lead only appeared in boundary layers approaching separation.

The decrease in the ratio of shear stress to kinetic energy has occurred in the majority of 3DBL experiments and appears to be a major stumbling block in the development of appropriate turbulence models. In some experiments the decrease is accompanied by an overall decrease in the turbulent kinetic energy. Both of these effects must be related to profound changes in the turbulence structure. Bradshaw and Pontikos [2] hypothesized that stress reductions are caused by the rotation of the dominant boundary layer eddies out of their preferred orientation by longitudinal vorticity. Anderson and Eaton proposed an alternative mechanism whereby the crossflow and the associated mean longitudinal vorticity interfere with the development of instantaneous longitudinal vortices that have been implicated as sources of turbulence production (see below). Unfortunately, there have been no detailed examinations (multipoint measurements or flow visualization) of the turbulence structure in 3DBLs which would provide the type of information needed to discriminate between these hypotheses.

A major sticking point in studying 3DBLs is that most measurements are conducted in flows which are inhomogeneous in the spanwise direction. In that case, it is difficult to trace the strain history that a given flow element experiences. An example is shown in Figure 2 which illustrates streamlines at various heights in a boundary layer approaching a strut. At the chosen profile measurement location, the streamline near the wall originated near the centerline while the freestream streamline originated far off the centerline. The pressure gradient is considerably different along these two streamlines.

In the area of heat transfer there are virtually no fundamental experiments including both heat transfer and fluid mechanics data on simple, attached 3DBLs. A number of experimental programs have provided heat transfer and fluids data in relatively complex geometries. Examples are the data around the base of a wall mounted strut by Goldstein and Karni [33] or the studies of flow in bent tubes by Baughn *et al.* [34]. In both of these experiments, the flow measurements have served to locate dominant features in the mean flow responsible for local heat transfer maxima. However, detailed measurements of the turbulent stress field have not been made.

Recently, Pauley and Eaton [7] made heat transfer and fluid mechanics measurements in a nominally 2D boundary layer made three-dimensional by a pair of embedded longitudinal vortices. This boundary layer is somewhat more complicated than the simple 3DBLs discussed above because there is a significant velocity component normal to the surface and three dimensional separation and attachment lines. * Nevertheless, there is a region directly beneath each vortex which appears very similar to an attached 3DBL. The mean velocity and temperature profiles were found to deviate markedly from the momentum and thermal laws of the wall respectively. Two-dimensional correlations for both the skin friction and Stanton number taken from Kays and Crawford [35] both fail badly in this region. The turbulent kinetic energy and the primary shear stress, $\overline{u'v'}$ were reduced substantially. All these changes suggest that there is a very significant modification of the boundary layer structure in the three dimensional region. The Pauley and Eaton data were sufficiently detailed that they could be numerically

* Note that the existence of 3D separation and reattachment lines does not imply the existence of reversed flow.

differentiated and used to test several turbulence models. A prescribed eddy viscosity model and two different 2-equation models were tested but all performed very poorly in the three-dimensional part of the flow.

Summarizing the state of knowledge in 3DBLs we find that there have been several careful experiments delineating the mean velocity and Reynolds stress development in specific 3D flow geometries. However, there are no experiments that include Reynolds stress measurements below about y^+ of 50, a crucial region governing heat transfer. Also, there has been only one experiment which included detailed heat transfer and fluid dynamics data for a 3DBL and that in a fairly complicated situation.

2.2 Flows on Rotating Disks

There have been a number of studies of the flow due to a rotating disk. For the purposes of discussion, the disk flow studies may be divided into free disks and confined disks. In this section attention will be focused on free disk flows, which may be further divided into those concerned with the fluid mechanics and those with the heat transfer.

Studies of the fluid flow near a rotating disk began with von Kármán [36] in which he applied similarity methods to solve for the laminar boundary layer on a disk of infinite radius spinning in a quiescent fluid. By assuming a $1/7$ power law for tangential component of the turbulent boundary layer profile he was also able to define a friction coefficient that depended on $Re^{-0.2}$. Von Kármán determined that the laminar boundary layer thickness was independent of position on the disk while the turbulent boundary layer thickness grew with the radius. The laminar boundary layer solutions were generated numerically by Cochran [37] and confirmed numerically by Gregory, Stuart and Walker [38] (within the uncertainty of the day).

At a local Reynolds number (based on the local radius and local disk speed) of approximately 1.5×10^5 the laminar boundary layer undergoes transition to a turbulent one as a result of the crossflow instability. The transition from a laminar boundary layer to a turbulent one has been studied analytically and experimentally by several investigators [38, 39, 40]. These works reveal transition as the formation of approximately 30 stationary (with respect to the disk) spiral vortices “whose radius decreases in the

direction of rotation" [38] and with their axes about 14° from the tangential direction. There is evidence [39, 40] that the number of vortices increases with increased radius (and Re). At a Re of approximately 2.9×10^5 the vortices become unstable; secondary vortices form in spirals around the primary ones before degenerating into turbulence.

Cham and Head [39] measured profiles of the mean velocity components of the turbulent boundary layer on a rotating disk and compared them to various calculation methods. They showed that while the tangential component profiles calculated by various methods were in reasonable agreement with their measurements, the crossflow profiles were not. The disagreement between the calculations and data for the crossflow velocity is important because the heat transfer is governed by the crossflow velocity. In this study there were no turbulence measurements.

The heat transfer from rotating disks has also been extensively studied [41-48]. The majority of these investigations are type 1 type experiments whose results are summarized as mean Nusselt numbers (Nu) and the effects due to changes in rotation rate. Their findings show that the average Nu for the disk goes as $Re^{0.5}$ in the laminar range, increases for Re greater than 1.5×10^5 and approaches a $Re^{0.8}$ dependence asymptotically as turbulence dominates the disk boundary layer. Richardson and Saunders [44] showed the importance of the crossflow velocity in determining the turbulent heat transfer. Using von Kármán's turbulent crossflow profiles and measured temperature profiles to calculate Nu , they find the calculated value to be far below the measured values. By altering the shape of the radial velocity profile they were able to demonstrate the importance of the radial flow to the heat transfer. McComas and Hartnett [47] measured temperature profiles in both laminar and turbulent flow. In the laminar regime their profiles agree with the predictions of Hartnett [48], and in the turbulent regime their profiles collapse on a $1/5$ power law. Popiel and Boguslawski [46] measured the local heat transfer coefficient to determine a local Nu as a function of local Re . Their findings show that for $Re < 1.95 \times 10^5$, $Nu = 0.33(Gr + Re^2)^{0.25}$, and for $1.95 \times 10^5 < Re < 2.5 \times 10^5$, $Nu = 10^{-19}Re^4$ and for $2.5 \times 10^5 < Re < 6.7 \times 10^5$ $Nu = 0.0188Re^{0.8}$. None of the above fluid mechanic or heat transfer studies contain turbulence measurements.

2.3 Summary of Relevant 2D Boundary Layer Research

In contrast to research on 3DBLs, there has been very extensive research on 2DBLs including single and multipoint measurements, measurements extending into the sublayer, qualitative and quantitative flow visualization, and direct numerical simulation. The literature is far too extensive to review here so we will just attempt to summarize a few key points that appear relevant to 3DBL research.

It is well established that the peak in turbulence production occurs very near the wall around $y^+ = 20$ (see Moser and Moin [49]) and is in some way associated with the bursting event described by Kim *et al.* [50]. The mechanism causing the burst events is still a subject of debate, but it seems obvious that hydrodynamic instability must play a role in the process. Numerous investigators have suggested the presence of streamwise vortices in the near-wall region (see the brief review by Bawirzanski *et al.* [51]) which may appear as the legs of a hairpin vortex, as a closely coupled counter-rotating vortex pair, or as single vortices. There is general agreement that the vortices are important in the production of turbulence and Blackwelder [52] has gone as far as suggesting a close analogy between the bursting process and the growth and breakdown of Gortler vortices in curved laminar boundary layers. Clearly then, we must be concerned with the interaction of such vortices with a cross flow. Anderson and Eaton [3] have hypothesized that the mean longitudinal vorticity present in a 3DBL interferes with the formation of turbulent longitudinal vortices of the opposite sign. If a significant fraction of the vortices are eliminated, one might expect the production of kinetic energy and shear stress to be reduced.

Summarizing, we have a good knowledge of mean flow and temperature profiles, single point turbulence statistics all the way into the sublayer, and structural information such as streak spacing and higher order statistics for two-dimensional boundary layers. This information offers an excellent base for comparison with the detailed data to be acquired in the present program.

3. OUTLINE OF OBJECTIVES

The general objectives of the research program then are to obtain detailed heat transfer, and fluid mechanics measurements in a simple three-dimensional boundary layer. Based on the above discussions the flow on a rotating disk in an otherwise quiescent environment was chosen because it produces a strongly three dimensional boundary layer with only two significant space coordinates (r, z) . It has the additional advantage that transition to turbulent flow produces an observable cross flow vortex structure which can be traced into the turbulent flow regime. Finally, the rotating disk flow has numerous technological applications in its own right including heat transfer to gas turbine disks, disk drive data storage devices, and other rotating machinery.

The research program will include single point measurements and coupled full field heat transfer measurements of sufficient detail to allow direct testing of models. Field measurements should be obtained at least into the lower part of the logarithmic layer ($y^+ = 50$) and closer if possible. Therefore an apparatus must be developed providing a reasonably thick boundary layer while still allowing close access for laser anemometry. Finally, flow visualization of the near-wall structure will be performed to examine differences between 2D and 3D boundary layers and also to observe the connection between transition structures and the turbulent boundary layer.

4. Experimental Plan

The proposed experiments include detailed measurements in the boundary layer on a single rotating disk in a quiescent room. Measurements will include the surface heat transfer coefficient, normal temperature profiles, mean velocity profiles, and the full Reynolds stress tensor. Higher order statistics and/or multipoint measurements will be used to study the boundary layer structure. In addition, flow visualization will be conducted in a water-flow apparatus which can be set up to simulate the target flow.

The expected flowfield is shown in Figure 3. The left side of the figure is a photograph of the flow and the right hand side shows profiles of the mean tangential and radial velocity components in the laminar regime. The left hand side of the figure shows

the four distinct regions in the flow. Moving outward from the axis, we see a region of stable laminar flow in the center of the disk, a annulus of laminar flow disrupted by crossflow vortices, an unstable transition region, and the fully turbulent region. Transition is expected to occur at a rotational Reynolds number ($\Omega R^2/\nu$) of about 280,000. Alternatively, a circular trip wire could be installed in the crossflow vortices region to create a more rapid transition to turbulence.

The basic experimental apparatus to be constructed is sketched in Figure 4. The apparatus consists of a 1 meter diameter steel disk mounted on a two-bearing spindle and driven by a variable speed motor. A fixed concentric annulus is installed to isolate the flows from the upper and lower surfaces. The entire assembly is mounted on a steel frame which can carry either a standard probe traverse mechanism or transmitting and receiving optics for a laser anemometer. This apparatus is quite similar to that used by Cham and Head with the major differences being the measurement systems employed. The experiment will be contained in a separate isolation room approximately 4 meters square by 3 meters high to avoid perturbations in the entrainment flow and to allow complete seeding of the entire flowfield.

The disk will be driven at speeds up to 1000 RPM to produce tip rotational Reynolds numbers up to 1.6×10^6 , well within the turbulent flow regime. Based on the experiments of Cham and Head, we expect a boundary layer thickness of approximately 4 mm in the laminar flow regime and approximately 20 mm in the fully turbulent regime. This will allow adequate resolution for multicomponent velocity measurements required to obtain the Reynolds stress components.

The first step of the research program will be to measure the heat transfer coefficient on the surface as a function of the rotational Reynolds number and the radial position. These measurements will be obtained using a specially developed, constant heat flux test surface sketched in figure 5. A 1.3 cm thick aluminum disk provides the structural base for the composite structure, with a 1.3 cm thick disk of phenolic mounted on top of it to minimize the back losses from the heater. The heater is an encapsulated heater consisting of a continuous copper strip laminated to a kapton backing. By maintaining a constant areal density of the copper over surface of the disk, a constant heat flux is

achieved. In order to smooth the slight local variations in the surface heat flux due to spacings between the copper heating strips, a thin aluminum plate will be mounted on top of the heater. The thickness of the top plate (0.3 cm) is chosen to be about ten times the distance between the copper heating strips. The cavity below the rotating disk will be heated electrically in order to decrease the start-up thermal transient. The temperature in the cavity will be maintained within 2° Celsius of the top surface temperature to control the back losses. Thermistors will be mounted into the top aluminum plate at four radial locations to obtain quantitative surface temperature measurements. To obtain a qualitative picture of the surface temperature distribution, liquid crystals will be applied to the surface. Preliminary uncertainty analysis using the surface temperature, the lab temperature, and the bottom cavity temperature along with the local disk speed, the surface emissivity and the power input as primary measurands indicates a 3-5% uncertainty in the calculated local Stanton number.

The heat transfer measurements will proceed rapidly once the debug and shakedown is complete so a reasonably large range of parameters can be investigated. Measurements will be made for tip rotational Reynolds numbers ranging from approximately 100,000 to 1.6 million. In the higher Reynolds number cases, measurements will be obtained for both tripped and untripped boundary layers. The trip will be a circular wire glued to the disk at a radius corresponding to a Reynolds number of approximately 200,000.

Following the work of Cham and Head, we expect to find that the heat transfer coefficient is a function only of the local rotational Reynolds number. If this is indeed the case, a single relatively high speed case will be selected for detailed measurements assuming that various rotational Reynolds numbers can be achieved simply by examining various radial positions. The detailed mapping will begin with single point measurements including profiles of the mean temperature, two-components of mean velocity, and the Reynolds stress tensor. These data will be measured with conventional probe techniques as described in detail by Pauley and Eaton [5] and summarized below.

The temperature field will be measured using a 0.08 mm diameter, butt-welded, Type K thermocouple mounted on a hotwire type stem. The probe has an effective measurement volume 0.4 mm long and has been used extensively in our boundary layer

heat transfer program. It is calibrated using a platinum resistance thermometer to reduce the uncertainty in the temperature measurements to approximately 0.1°C . The mean velocity will be measured using a three-hole cobra probe fabricated using 0.8 mm diameter stainless-steel tubes following the recommendations of Bryer and Pankhurst [53]. A calibration technique was developed for this probe allowing yaw angle measurements with an uncertainty of around 1 degree in the non-nulling mode. Finally the full Reynolds stress tensor, the turbulent triple products, and a redundant measurement of the mean velocity will be obtained using a rotatable cross-wire probe. The probe is aligned with the mean velocity vector at each point minimizing the uncertainty due to out-of-plane velocity components. We have extensive experience with this measurement technique and expect uncertainty of the order of 5% in the normal stresses, 10% in the primary shear stress, $\overline{u'v'}$, and 15% in the cross-stream shear stress, $\overline{v'w'}$. All three probes will be actuated using the two-axis, stepper motor driven traverse gear developed for our present 3DBL research program.

There are two problems with the single point measurements discussed above. One is that probe measurements in rotating flows are suspect because the probe may be operating in its own wake. In the present case, there is a significant radial flow so probe interference may not be important. However, this should be confirmed using non-intrusive measurements. The second problem has to do with vertical resolution. As mentioned in the Introduction, the near-wall region, typically below y^+ of 100 is critical in controlling the heat transfer rates. Three dimensional boundary layer measurements in this region are rare so it seems imperative to produce near-wall data in this new experiment.

Both problems will be addressed by using a two-component Laser Doppler Anemometer (LDA) to duplicate and extend the probe measurements. A two-color, four beam LDA system will be used to simultaneously measure two-components of the velocity. The system is sketched in Figure 6 which shows the transmitting optics set up in two different orientations. In position 1, the transmitting optics are set up to simultaneously measure the tangential and normal velocity components u and v . In position 2 the system measures the radial (w) and normal velocity components. Therefore 5 of

the 6 independent components of the Reynolds stress tensor can be measured directly. The sixth component ($\overline{u'w'}$) is generally considered to be unimportant in 3DBLs since streamwise and spanwise gradients are always small relative to normal gradients. Probe measurements of $\overline{u'w'}$ will be available and the LDA system may be reconfigurable to measure it if necessary.

The LDA receiving optics will be mounted above the disk in a forward/scattering off-axis collection mode. This mode will allow the vertical extent of the measurement volume to be minimized by using an appropriate pinhole. Again assuming the boundary layer state to be a function only of the local rotational Reynolds number, the LDA will be set up to make measurements at a single radial position with the Reynolds number changed by changing the disk speed. Selecting a location near the disk periphery (around $r/R = 0.8$) will allow us to use a relatively short focal length lens (450 mm) and obtain a measurement volume diameter and length of less than 90 microns and 600 microns respectively. It may be possible to reduce these dimensions even further by using a pinhole on the receiving optics. At a rotational Reynolds number of 1 million and a radius of 0.4 m, the size of one viscous wall unit (ν/u_τ) will be approximately 10 microns. Therefore, we can expect reasonably resolved measurements in the lower part of the logarithmic region. Lower Reynolds number will provide even better resolution.

A uniform distribution of seeding particles is key to obtaining reliable laser anemometry measurements. To facilitate this, the entire apparatus will be operated in a closed room with filtered vents. All of the air in the room will be seeded prior to a data run. The seed will be either polystyrene or Titanium-dioxide particles approximately 1 micron in diameter and will be dispersed using airbrush paint sprayers.

The single point data will be analyzed by comparing it to various levels of models developed for 2D boundary layer data. For example, the mean velocity and temperature profiles will be compared to the well known law-of-the-wall profiles and the heat transfer measurements compared to 2D correlations. The turbulence statistics including the Reynolds stresses, the dissipation rate, and triple products will be compared to established 2D data. There will be particular emphasis on assessing the Bradshaw [2] description of stress modification by three dimensionality. Do the stress reductions

observed in other 3DBL's occur in the disk flow and if so, can they be explained by a simple rotation of the stress tensor? Finally, the data will be compared to modern turbulence models including the popular $k-\epsilon$ model. All of the terms in this model can be measured directly providing a good test of the model accuracy.

The single point measurements will be followed by a set of first cut experiments to examine the boundary layer structure. There has never been any significant study of the instantaneous structure in 3D turbulent boundary layers so the exact course of this research is difficult to determine prior to the first experiments. Both qualitative flow visualization and quantitative measurement of temporal and multipoint statistics will be used to gain the first insight into the structure. The flow visualization experiments will be conducted in an existing rotating water flow apparatus that has been previously used by Abrahamson *et al.* [54,55] and Nordquist *et al.* [56] to investigate the flow in disk drive data storage devices and turbine disk cavities. The apparatus consists of a driven spindle rotating a stack of 112 cm diameter glass disks in a rectangular closed chamber. Rotational Reynolds numbers up to 2 million can be attained and a tip Re of 1×10^6 is achieved at a disk speed of only 30 RPM. Therefore dye or hydrogen bubble visualization can be observed with the naked eye and recorded using conventional video or still photography. Visualization can be recorded in either a fixed laboratory reference frame or in a rotating reference frame.

All but the bottom disk will be removed to model the air flow apparatus. The closed geometry will not precisely model the air flow apparatus but the spacing between the disk surface and the fixed top cover will be approximately 20% of the disk radius so the interaction between the two boundary layers should be small. We can expect the qualitative features of the boundary layer to be similar in the two experiments.

Dye will be injected at the disk surface in the laminar region near the hub and allowed to flow outward in the boundary layer. Also, a hydrogen bubble wire will be stretched along a radial line near the disk surface in the turbulent region. The dye is expected to collect into the spiral vortices caused by the crossflow instability and be convected into the turbulent region. The hydrogen bubbles will allow examination of the flow structure within the fully turbulent region. The key questions are, does the so-

called streaky structure observed beneath two-dimensional boundary layers exist and if so, what is the radial (spanwise) spacing of the structures. Also, are the breakdown mechanisms and the longitudinal (tangential) extent of the streaky structures similar to those found in 2DBLs. These experiments should provide information needed to test the Anderson/Eaton hypothesis regarding stress reduction in 3DBLs.

A final matter of interest is the relation between the spiral vortices in the transition region and streaky structures within the turbulent region? At first glance, we expect the spacing of the spiral vortices to be about 6 times larger than the spacing of the boundary layer streaks if the latter is calculated using two-dimensional correlations (λ^+ is approximately 100). However, Anderson and Eaton [3] have made the argument that the near wall structure may be considerably altered by even mild three-dimensionality and implied that the streak spacing would become larger. In any case, the fate of the spiral vortices within the turbulent boundary layer will be of interest.

The quantitative structural measurements cannot be completely defined prior to the completion of the visualization work. We anticipate using primarily probe measurements because continuous signals are available and multipoint measurements are considerably easier than with LDA systems. One advantage of the moving surface boundary condition is that structures fixed to the surface are swept past a fixed probe and spectral measurements can be used to deduce the spatial structure. For example, the crossflow instability produces vortices tilted approximately 14° from the tangential direction. Previous work shows that the vortices are essentially fixed to the disk surface. Visualizations are expected to confirm this, and therefore the vortex spacing can be measured by installing a single hotwire probe oriented to measure the tangential velocity component and taking the power spectrum of the resulting signal. The sublayer streaks are also expected to be tilted at a small angle and their mean spacing should be measureable using the same technique.

Summarizing the research program, we expect to supply detailed surface and field data allowing direct testing and development of models for three dimensional boundary layers. Qualitative and quantitative structural information will also provide unique new insight into the physics of turbulence production and heat transport in complex flows.

EQUIPMENT ITEM IN BUDGET

An existing TSI high power single-component LDA system will be upgraded to a two-component system for this research. The single component system includes a 2W argon-ion laser, 3.75X beam expander, a 150 mm diameter by 450 mm focal length transmitting lens, and forward scattering collection optics. The requested components will be used to upgrade this system to a two-color, four-beam system. A compatible signal processor for the second component will be borrowed from another project in the laboratory. With the large beam expander and transmitting lens the upgraded system will provide simultaneous two-component measurements with the required spatial resolution.

The existing system can be used to measure any velocity component and the normal stresses directly. However, a complex and questionable two-step measurement procedure would be required to obtain the shear stress components. Also, there would be no possibility of measuring instantaneous values of the shear stresses if the need arose. While the research could proceed without the LDA upgrade it would be considerably enhanced by the addition of a second component.

SUPPORTING FACILITIES

The Heat Transfer and Turbulence Mechanics laboratory at Stanford is fully equipped to build the equipment and to conduct the experiments required for this research. An extensive collection of pressure and hotwire probes and associated automatic traversing mechanisms are dedicated to the 3DBL project. An existing, high-power, single-component LDA system will be upgraded to a two-component system and dedicated to this research. Three multicomponent LDA systems and two single component systems all manufactured by TSI are in use in the lab. Therefore the lab is well stocked with extra optical components, digital storage oscilloscopes, laser power meters, and special purpose software for LDA systems.

The water flow rotating disk apparatus described in Section 4 is fully operational and available for use. Various flow visualization hardware including dye injectors, lighting systems, still and video cameras, and a hydrogen bubble generator are dedicated to the

apparatus. The portable laser sheet described by Koga *et al.* [57] was developed for this apparatus and is available for use.

The project will be well supported by computer facilities. The existing 3DBL wind-tunnel is supported by an IBM PC-AT and a Masscomp 5600 for wind tunnel control, data acquisition, data processing, and displaying of results. In addition, the dedicated computers are networked to the other computers in the lab including two other Mass-comp workstations, 2 VAX computers, and a Silicon Graphics IRIS workstation.

PERSONNEL

Information on the Principal Investigator is contained in the attached curriculum vitae. Most of the research will be conducted by a PhD candidate Research Assistant under the supervision of the Principal Investigator. Up to three MS level students will also participate in the research at no cost.

REFERENCES

1. Proceedings of the Zoran Zaric Memorial Int'l Seminar on Near-Wall Turbulence, Dubrovnik, Yugoslavia, May 1988
2. Bradshaw, P., and N. S. Pontikos, "Measurements in the Turbulent Boundary Layer on an 'Infinite' Swept Wing," J. Fluid Mech., Vol. 159, 1985, pp. 105-130.
3. Anderson, S. D., and J. K. Eaton, "Reynolds Stress Development in Pressure-Driven Three-Dimensional Turbulent Boundary Layers," J. Fluid Mech., in press 1988.
4. Launder, B.E. "On the Computation of Convective Heat Transfer in Complex Turbulent Flows," J. Heat Transfer, Vol. 110, pp. 1112-1128.
5. Eibeck, P. A., and J. K. Eaton, "Heat Transfer Effects of a Longitudinal Vortex Embedded in a Turbulent Boundary Layer," J. Heat Transfer, Vol. 109, No. 1, Feb. 1987, pp. 16-24.
6. Eibeck, P. A., and J. K. Eaton, "The Effects of Longitudinal Vortices Embedded in a Turbulent Boundary Layer on Momentum and Thermal Transport," Proceedings of 8th International H.T. Conference, San Francisco, 1986, pp. 1115-1120.
7. Pauley, W. R., and J. K. Eaton, The Fluid Dynamics and Heat Transfer Effects of Streamwise Vortices Embedded in a Turbulent Boundary Layer, Rept. MD-51, Dept. of Mechanical Engineering, Stanford University, August 1988.
8. Pauley, W. R., and J. K. Eaton, "Experiments on the Development of Longitudinal Vortex Pairs Embedded in a Turbulent Boundary Layer," AIAA J., Vol. 26, 1988 pp. 816-823.
9. Pauley, W. R., and J. K. Eaton, "The Effect of Embedded Longitudinal Vortex Pairs on Turbulent Boundary Layer Heat Transfer," Proceedings of 2nd International Symposium on Transport Phenomena in Turbulent Flows, Tokyo, 1987, pp. 269-282.
10. Anderson, S. D., and J. K. Eaton, "Experimental Study of a Pressure-Driven, Three-Dimensional, Turbulent Boundary Layer," AIAA J., Vol. 25, No. 8, Aug. 1987, pp. 1086-1092.
11. Anderson, S. D., and J. K. Eaton, An Experimental Investigation of Pressure Driven Three-Dimensional Turbulent Boundary Layers, Rept. MD-49, Thermosciences Division, Dept. of ME, Stanford Univ., June 1987.
12. Driver, D. M., and S. K. Hebbbar, "Experimental Study of a Three-Dimensional, Shear-Driven Turbulent Boundary Layer using a Three-Dimensional Laser Doppler Velocimeter," A1AA-85-1610, 1985.
13. Johnston, J. P., Experimental Studies in Three-Dimensional Boundary Layers, Stanford Univ. Thermosci. Div. Rep. Report MD-34, 1976.
14. Squire, H. B., and K. G. Winter, "The Secondary Flow in a Cascade of Airfoils in a Nonuniform Stream," J. Aero. Sciences, Vol. 18, 1951, pp. 271-277.

15. Senoo, Y., and M. Nishi, "Equilibrium Three-Dimensional Turbulent Boundary Layer on End Wall of a Curved Channel," 2nd Int'l JSME Symposium, Fluid Machinery and Fluidics, Tokyo, 1972.
16. Pierce, F. J., J. E. McAllister, and M. H. Tennant, "A Review of Near-Wall Similarity Models in Three-Dimensional Turbulent Boundary Layers," J. Fluids Engrg., Vol. 105, 1983, pp. 251-256.
17. Pierce, F. J., J. E. McAllister, and M. H. Tennant, "Near-Wall Similarity in a Pressure-Driven Three-Dimensional Turbulent Boundary Layer," J. Fluids Engrg. Vol. 105, 1983, pp. 257-262.
18. Johnston, J. P. "On the Three-Dimensional Turbulent Boundary Layer Generated by Secondary Flow," J. Basic Engrg., Vol. 82, 1960, pp. 233-248.
19. Rogers, B. K., and M. R. Head, "Measurement of Three-Dimensional Boundary Layers," The Aeronautical J., Vol. 73, 1969, pp. 796-798.
20. Vermeulen, A. "Measurements of Three-Dimensional Turbulent Boundary Layers," Ph.D. Thesis, Cambridge University, 1971.
21. Prahlad, T. S. "Mean Velocity Profiles in Three-Dimensional Incompressible Turbulent Boundary Layers," AIAA J., Vol. 11, 1973.
22. Klinksiek, W. F., and F. J. Pierce, "Simultaneous Lateral Skewing in a Three-Dimensional Turbulent Boundary-Layer Flow," J. Basic Engrg., Vol. 92, 1970, pp. 83-92.
23. Van den Berg, B., A. Elsenaar, and J. P. F. Lindhout, "Measurements in an Incompressible Three-Dimensional turbulent Boundary Layer, Under Infinite Swept Wing Conditions, and Comparison with Theory," J. Fluid Mech. Vol 70, 1975, pp. 127-148.
24. Johnston, J. P., "Measurements in a Three-Dimensional Turbulent Boundary Layer Induced by a Swept, Forward-Facing step," J. Fluid Mech., Vol. 42, 1970, pp. 823-844.
25. East, L. F., and W. G. Sawyer,, "Measurements of the Turbulence Ahead of a 45 Degree Swept Step Using a Double Split-Film Probe," Royal Aircraft Establishment TR 79136, 1979
26. Baskaran, V., and P. Bradshaw, "Experimental Investigation of a Three-Dimensional Turbulent Shear Layer over an 'Infinite' Swept Concave Surface," Proceedings 6th Sym. of Turbulent Shear Flows, Toulouse, France, 1987.
27. Baskaran, V. and P. Bradshaw, "Experimental Investigation of a Three-Dimensional Boundary Layer on an 'Infinite' Swept Concave Wing," Imperial College of Science and Tech., Aeronautics Dept., Final Report, 1987b.
28. Dechow, R. and K. O. Felsch, "Measurements of the Mean Velocity and of the Reynolds Stress Tensor in a Three-Dimensional Turbulent Boundary Layer Induced by a Cylinder Standing on a Wall," Proceedings Symposium on Turbulent Shear Flows, University Park, Pennsylvania, Vol. I, April 1977.

29. Ezekwe, C. I., F. J. Pierce, and J. E. McAllister, "Measured Reynolds Stress Tensors in a Three-Dimensional Turbulent Boundary Layer," AIAA J., Vol. 16, 1978, pp. 645-646.
30. Fernholz, H. H. and J. D. Vagt, "Turbulence Measurements in an Adverse-Pressure-Gradient Three-Dimensional Turbulent Boundary Layer along a Circular Cylinder," J. Fluid Mech., Vol. 111, 1981, pp. 233-269.
31. Muller, U. R., "Measurement of the Reynolds Stresses and the Mean-Flow Field in a Three-Dimensional Pressure-Driven Boundary Layer," J. Fluid Mech. Vol. 119, 1982, pp. 121-153.
32. Van den Berg, B., "Some Notes on Three-Dimensional Turbulent Boundary Layer Data and Turbulence Modelling," in Three-Dimensional Turbulent Boundary Layers, IUTAM Symposium (Fernholz, H.H. and Krause, E., eds.) Springer-Verlag, 1982.
33. Goldstein, R. J., and J. Karni, "The Effect of a Wall Boundary Layer on Local Mass Transfer from a Cylinder in Crossflow," J. Heat Transfer, Vol. 106, 1984, pp. 260-267.
34. Baughn, J. W., H. Iacovides, D. C. Jackson, and B. E. Launder, "Local Heat Transfer Measurements in Turbulent Flow Around a 180-deg Pipe Bend," J. Heat Transfer, Vol. 109, 1987, pp. 43-48.
35. Kays, W. M., and M. E. Crawford, Convective Heat and Mass Transfer, McGraw-Hill, New York, 1980.
36. von Karman, T., "Uber Laminare Und Turbulente Reibung," Zeitschrift Fur Angewandte Mathematik Und Mechanik, Vol. 1, 1921, pp. 233-252
37. Cochran, W. G., "Flow Due to a Rotating Disc," Proceedings Camb. Phil. Soc., Vol. 30., 1934, p. 365.
38. Gregory, N., J. T. Stuart, and W. S. Walker, "On the Stability of Three-Dimensional Boundary Layers with Application to the Flow due to a Rotating Disk," Phil. Trans. of Royal Soc. of London, Vol. 248, 1955, pp. 155-199.
39. Malik, M. R., and S. A. Orzag, "Instability and Transition in Rotating Disk Flow," AIAA Journal, 19:9., 1981, pp. 1131-1138.
40. Kohama, Y., "Crossflow Instability in Rotating Disk Boundary-Layer," AIAA-87-1340, 1987.
41. Cobb, E.C., and O. A. Saunders , "Heat Transfer from a Rotating Disk," Proceedings of the Royal Soc. Ser A 236, 1956, pp. 343-351.
42. Young, R. L., "Heat Transfer from a Rotating Plate," Trans ASME, Vol. 78, 1956, pp. 1163-1168.
43. Kreith F., J. H. Taylor, and J. P. Chong, "Heat and Mass Transfer from a Rotating Disk," J. Heat Transfer, Vol. 81, 1959, pp. 95-105.
44. Richardson, P. D., and O. A. Saunders, "Studies of Flow and Heat Transfer Associated with a Rotating Disc," J. of Mech. Eng. Sci. 5:4., 1963, pp. 336-342.

45. Metzger, D. E., "Heat Transfer and Pumping on a Rotating Disk with Freely Induced and Forced Cooling," J. Eng for Power, 1970, pp. 342-348.
46. Popiel, Cz.O., and L. Boguslawski, "Local Heat-Transfer Coefficients on the Rotating Disk in Still Air," Int'l. J. Heat Mass Transfer, Vol. 18, 1975, pp. 167-170.
47. McComas, S. T., and J. P. Hartnett (1970) "Temperature Profiles and Heat Transfer Associated with a Single Disk Rotating in Still Air," Proceedings 4th Ann. Int'l. Heat Trans. Conference.
48. Hartnett, J. P., "Heat transfer from a non-isothermal disk rotating in still air," J. Appl. Mech., Vol. 26, 1959, pp. 672-673.
49. Moser, R. D., and P. Moin, "The Effects of Curvature in Wall-Bounded Turbulent Flows," J. Fluid Mech., Vol. 175, 1987, pp. 479-510.
50. Kim, H. T., S. J. Kline, and W. C. Reynolds, "The Production of Turbulence Near a Smooth Wall in a Turbulent Boundary Layer," J. Fluid Mech. Vol. 50, 1971, pp. 133-160.
51. Bawirzanski, E., M. Randolph, and H. Eckelmann, "Direct Measurement of Streamwise Vorticity Fluctuations with a Cylinder Probe," Proceedings 2nd Int'l Symp. on Transport Phenomena in Turbulent Flows, Tokyo, 1987, pp. 605-612.
52. Blackwelder, R.F. "Analogies between Transitional and Turbulent Boundary Layers," Phys. Fluids, Vol. 26, 1983, p. 2807.
53. Bryer, D. W., and R. C. Pankhurst, Pressure-Probe Methods for Determining Wind Speed and Flow Direction, Her Majesty's Stationary Office, London, 1971.
54. Abrahamson, S. D., J. K. Eaton, and D. J. Koga, "The Flow Between Shrouded Corotating Disks," Physics of Fluids, in press 1988.
55. Abrahamson, S. D., D. J. Koga, and J. K. Eaton, An Experimental Investigation of the Flow Between Shrouded Corotating Disks, Rept. MD-50, Dept. of Mechanical Engineering, Stanford University, April 1988.
56. Nordquist, J.S., S. D. Abrahamson, J. Wechkin, and J. K. Eaton, Visualization Studies in Rotating Disk Cavity Flows, Rept. IL-98, Dept. of Mech. Engrg. Stanford U., 1988.
57. Koga, D.J., S. D. Abrahamson, and J. K. Eaton, "Development of a Portable Laser Sheet," Experiments in Fluids, Vol. 5, 1987, pp. 215-216.

Figure 1. General Profile Shape for a Three-Dimensional Turbulent Boundary Layer Shown in Coordinates Aligned with the Freestream Velocity

Figure 2. Streamlines in the Near-Wall and Freestream Planes of the Flow Approaching a Strut. Adapted from Dechow and Felsch [28].

Boundary Layer Flow Visualization

Laminar Velocity Profiles
(Rotating Reference Frame)

Figure 3 Disk Boundary Layer Flow

Figure 4. Experimental Apparatus

Figure 5 Heat Transfer Surface Design

Side View (Position 1)

Figure 6. Schematic of Laser Doppler Anemometer

Curriculum Vitae

John K. Eaton

Education: Stanford University, Stanford, California

9/72-6/76 Bachelor of Science in Mechanical Engineering

9/76-3/77 Master of Science in Mechanical Engineering.

3/77-6/80 Ph.D. degree in Mechanical Engineering. Thesis work was an experimental study of a reattaching turbulent shear layer.

Professional Experience:

1988-present Associate Professor and Associate Chairman, Department of Mechanical Engineering, Stanford University

1986-1988 Associate Professor, Department of Mechanical Engineering Stanford University. Director of Heat Transfer and Turbulence Mechanics Laboratory.

1/87-7/87 SERC Visiting Fellow, Department of Aeronautics, Imperial College of Science and Technology, London.

1980-1985 Assistant Professor, Department of Mechanical Engineering, Stanford University.

Industrial Experience:

Summers 1975-76 Mechanical Engineer, Hewlett Packard, San Diego Div.
Summer 1974 Engineer, AiResearch Manufacturing Co., Phoenix, AZ

Consulting: Experimental fluid mechanics and heat transfer design primarily for disk drive, gas turbine and hydraulic power companies.

Research:

Supervise and participate in research in four major areas. Currently supervise one Senior Research Associate, 2 post-doctoral fellows, and six Ph.D. students. Six Ph.D.'s have been completed under my supervision.

1. Active control of separated flows: This set of projects attempts to identify and modify large structures of separated flows in real time.
2. Flow and heat transfer in three-dimensional boundary layers. Involves detailed measurements of turbulence structure and heat transfer in boundary layers with introduction of well controlled three-dimensional perturbations.

3. Fundamental studies of particle laden flows: Physical and numerical experiments on the interaction of dispersed solid particles with gas-phase turbulence.
4. Flows in rotating systems: The present focus is on flow related to disk drive data storage devices.

Teaching and Departmental Service:

Teach undergraduate and graduate courses in heat transfer, fluid mechanics, experimental methods, and computer interfacing. Associate Chairman, Committee on Undergraduate Studies-Subcommittee on Evaluation and Improvement in Teaching, President, Stanford Sigma Xi.

Awards and Honors:

University Fellow (1988-90)

NSF Presidential Young Investigator Award

GM Fellow (PYI Matching Grant)

Stanford Tau Beta Pi Award for Excellence in Undergraduate Teaching

National Science Foundation Three-Year Graduate Fellowship

Silver Medal Award from the Royal Society of the Arts

Member of the Tau Beta Pi, Phi Beta Kappa, and Sigma Xi

AIAA Survey Paper Citation

Publications:

Fully Refereed Journal Articles and Equivalent:

1. Eaton, J. K., A. H. Jeans, J. Ashjaee, and J. P. Johnston, "A Wall-Flow-Direction Probe for Use in Separating and Reattaching Flows," Trans. ASME, J. Fluids Engrg., 101, No. 3, Sept. 1979, pp. 364-366.
2. Eaton, J. K., and J. P. Johnston, "A Review of Research on Subsonic Turbulent Flow Reattachment," AIAA J., 19, No. 9, Sept. 1981, pp. 1093-1100.
3. Westphal, R., J. K. Eaton, and J. P. Johnston, "A New Probe for Measurement of Velocity and Wall Shear Stress in Unsteady, Reversing Flow," J. Fluids Engrg., 102, No. 3, Sept. 1981, pp. 478-482.
4. Eaton, J. K., R. V. Westphal, and J. P. Johnston, "Two New Instruments for Flow-Direction and Skin-Friction Measurements in Separated Flows," ISA Transactions, 21, No. 1, 1982, pp. 69-78.
5. Eaton, J. K., and J. P. Johnston, "Low Frequency Unsteadiness of a Reattaching Turbulent Shear Layer," Turbulent Shear Flows III (Durst et al., eds.), Springer-Verlag, 1982.
6. Adams, E. W., J. K. Eaton, and J. P. Johnston, "An Examination of Velocity Bias in a Highly Turbulent Separated and Reattaching Flow," Laser Anemometry in Fluid Mechanics-II, Adrian et al. eds., Ladoan, Lisbon, 1984, pp. 21-37.
7. Kale, S. R., and J. K. Eaton, "An Experimental Investigation of the Effects of Diffusers on Elutriation Rates from Fluidized Beds," Gas-Solid Flows, ASME Pub. FED, 10, (J. Jurewicz, ed.), pp. 107-114.
8. Kale, S. R., and J. K. Eaton, "An Experimental Investigation of Gas-Particle Flows through Diffusers in the Freeboard Region of Fluidized Beds," J. Multiphase Flow, Vol. 11, No. 5, Oct. 1985, pp. 659-674.
9. Vogel, J. C., and J. K. Eaton, "Combined Heat Transfer and Fluid Dynamic Measurements Downstream of a Backward-Facing Step," ASME, J. Heat Transfer, Vol. 107, No. 4, Nov. 1985, pp. 922-929.
10. Eibeck, P. A., and J. K. Eaton, "The Effects of Longitudinal Vortices Embedded in a Turbulent Boundary Layer on Momentum and Thermal Transport," Proceedings of 8th International H.T. Conference, San Francisco, 1986, pp. 1115-1120.
11. Eibeck, P. A., and J. K. Eaton, "Heat Transfer Effects of a Longitudinal Vortex Embedded in a Turbulent Boundary Layer," J. Heat Transfer, Vol. 109, No. 1, Feb. 1987, pp. 16-24.

12. Westphal, R. V., J. K. Eaton, and W. R. Pauley, "Interaction Between a Vortex and a Turbulent Boundary Layer in a Streamwise Pressure Gradient," Turbulent Shear Flows 5., Springer-Verlag, 1987, pp. 266-277.
13. Koga, D. J., S. D. Abrahamson, and J. K. Eaton, "Development of a Portable Laser Sheet," Experiments in Fluids, Vol. 5, No. 3, 1987, pp. 215-216.
14. Anderson, S. D., and J. K. Eaton, "Experimental Study of a Pressure-Driven, Three-Dimensional, Turbulent Boundary Layer," AIAA J., Vol. 25, No. 8, Aug. 1987, pp. 1086-1092.
15. Pauley, W. R., and J. K. Eaton, "The Effect of Embedded Longitudinal Vortex Pairs on Turbulent Boundary Layer Heat Transfer," Proceedings of 2nd International Symposium on Transport Phenomena in Turbulent Flows," Tokyo, 1987, pp. 269-282.
16. Abrahamson, S. D., D. J. Koga, and J. K. Eaton, "Flow Visualization and Spectral Measurements in a Simulated Rigid Disk Drive," IEEE Transactions on Components, Hybrids and Manufacturing Tech., Vol. 11, 1988.
17. Pauley, W. R., and J. K. Eaton, "Experiments on the Development of Longitudinal Vortex Pairs Embedded in a Turbulent Boundary Layer," AIAA J., Vol. 26, 1988, pp. 816-823.
18. Adams, E. W., and J. K. Eaton, "An LDA Study of the Backward-Facing Step Flow Including the Effects of Velocity Bias," J. Fluids Engineering, Vol. 110, pp. 275-282.
19. Anderson, S. D., and J. K. Eaton, "Reynolds Stress Development in Pressure-Driven Three-Dimensional Turbulent Boundary Layers," J. Fluid Mech., in press 1988.
20. Abrahamson, S. D., J. K. Eaton, and D. J. Koga, "The Flow Between Shrouded Corotating Disks," Physics of Fluids, in press 1988.

Invited Review Papers (selected by international committee):

1. Eaton, J. K., and J. P. Johnston, "Data Evaluation--Subsonic Backward-Facing Step Flow," Vol. I, Proceedings of the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows: Comparison of Computation and Experiment, 1980.
2. Eaton, J. K., "An Overview of the Predictive Test Cases," Vol. I, Proceedings of the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows: Comparison of Computation and Experiment, 1980.
3. Eaton, J. K., "Summary of Computations for Cases 0421, 0431, P2 and P3, Separated Internal Flows," Vol. III, Proceedings 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows: Comparison of Computation and Experiment, 1982.

Other Papers:

1. Eaton, J. K., A. H. Jeans, and J. P. Johnston, "Measurements in a Reattaching Turbulent Shear Layer," Proceedings of the 2nd Symposium on Turbulent Shear Flows, London, July 1979.

2. Vogel, J. C., J. K. Eaton, and E. W. Adams, "Combined Heat Transfer and Fluid Dynamic Measurements Behind a Backward-Facing Step," ASME Paper 83-WA/HT-11.
3. Eaton, J. K., and A. E. Alving, "Natural Unsteadiness of a Separation Bubble Behind a Backward Facing Step," AFOSR Workshop on Unsteady Separated Flow, Air Force Academy, 1983.
4. Eibeck, P. A., and J. K. Eaton, "Heat Transfer Effects of Longitudinal Vortices Embedded in a Turbulent Boundary Layer," ASME Paper 84-HT-21, 1984.
5. Vogel, J. C., and J. K. Eaton, "The Transport of Heat in a Turbulent Reattaching Flow," 5th International Symposium on Turbulent Shear Flows, Cornell University, 1985.
6. Anderson, S. D., and J. K. Eaton, "Reynolds Shear Stress Development in Pressure Driven Three-Dimensional Turbulent Boundary Layers," Proceedings of 6th Symposium on Turbulent Shear Flows, Toulouse, France, 1987.
7. Koga, D. J., C. F. Nelson, and J. K. Eaton, "A New Program for Active Control of Unsteady, Separated Flow Structures," Proceedings of AFOSR Unsteady Separated Flow Workshop, July 1987.
8. Eaton, J. K., W. R. Pauley, and S. D. Anderson, "Heat Transfer in Three-Dimensional Turbulent Boundary Layers," Sixth Symposium on Energy Engineering Sciences, Argonne National Laboratory, 1988.
9. Abrahamson, S. D., D. J. Koga, and J. K. Eaton, "Flow in a Simulated Rigid Disk Drive," ASME Vol. FED-Vol 54, pp. 13-16.
10. Squires, K. D., and J. K. Eaton, "Study of the Effects of Particle Loading on Homogeneous Turbulence using Direct Numerical Simulation," to be presented International Symposium on Turbulence Modification in Dispersed Multiphase Flows, San Diego, July 1989.
11. Rogers, C. B., and J. K. Eaton, "The Response of Solid Particles in a Vertical Turbulent Boundary Layer in Air," submitted to International Journal of Multiphase Flow, 1988.
12. Rogers, C. B., and J. K. Eaton, "Particle Response and Turbulent Modification in a Flat Plate Turbulent Boundary Layer," to be presented to International Symposium on Turbulence Modification in Dispersed Multiphase Flows, San Diego, July 1989.
13. Longmire, E. K., and J. K. Eaton, "Active Control of Particle Dispersion and Turbulence Level in a Round Jet," submitted to 7th Symposium on Turbulent Shear Flows, Stanford, August 1989.
14. Abrahamson, S. D. and J. K. Eaton, "An Analysis of Boundary Layers in Rotating Disk Flow," submitted to Physics of Fluids, 1988.
15. Nordquist, J. S., S. D. Abrahamson, J. Wechkin, and J. K. Eaton, "Visualization Studies in Rotating Disk Cavity Flows," submitted to ASME Journal of Turbomachinery, 1988.
16. Eaton, J. K., "Interpretation and Communication of Heat Transfer Measurements in Three-Dimensional Turbulent Boundary Layers," NSF Workshop on Processing of Large Data Sets in Combustion and Heat Transfer, October 1988.

17. Eaton, J. K., J. P. Johnston, and D. J. Koga, "Active Control of Separating and Fully Separated Flows," Proceedings of AFOSR Conference on Turbulence, USC, June 1988.
18. Pauley, W. R., J. K. Eaton, and A. D. Cutler, "Diverging Boundary Layers with Zero Streamwise Pressure Gradient," AIAA 27th Aerospace Sciences Meeting, January 1989. Submitted to AIAA J.
19. Nelson, C. F., D. J. Koga, and J. K. Eaton, "Unsteady, Separated Flow Behind an Oscillating Two-Dimensional Flap" AIAA 27th Aerospace Sciences Meeting, January 1989. Submitted to AIAA J.

Technical Reports

1. Eaton, J. K., "Turbulent Flow Reattachment: An Experimental Study of the Flow and Structure Behind a Backward-Facing Step," Report MD-39, Department of Mechanical Engineering, Stanford University, June 1980.
2. Westphal, R. V., J. P. Johnston, and J. K. Eaton, "Experimental Study of Flow Reattachment in a Single-Sided Sudden Expansion," NASA CR 3765, 1984.
3. Adams, E. W., J. P. Johnston, and J. K. Eaton, "Experiments on the Structure of Turbulent Reattaching Flows," Report MD-43, Department of Mechanical Engineering, Stanford University, June 1984.
4. Vogel, J. C., and J. K. Eaton, "Heat Transfer and Fluid-Mechanics Measurements in the Turbulent Reattaching Flow Behind a Backward-Facing Step," Report MD-44, Department of Mechanical Engineering, Stanford University, June 1984.
5. Kale, S. R., and J. K. Eaton, "An Experimental Investigation of Gas-Particle Flows through Diffusers in the Freeboard Region of Fluidized Beds," Report MD-45, Department of Mechanical Engineering, Stanford University, June 1984.
6. Eibeck, P. A., and J. K. Eaton, "An Experimental Investigation of the Heat-Transfer Effects of a Longitudinal Vortex Embedded in a Turbulent Boundary Layer," Report MD-48, Department of Mechanical Engineering, Stanford University, November 1985.
7. Westphal, R. V., W. R. Pauley, and J. K. Eaton, "Interaction Between a Vortex and a Turbulent Boundary Layer," NASA TM 88361, January 1987.
8. Anderson, S. D., and J. K. Eaton, "An Experimental Investigation of Pressure Driven Three-Dimensional Turbulent Boundary Layers," Report MD-49, Thermosciences Division, Department of Mechanical Engineering, Stanford University, June 1987.
9. Abrahamson, S. D., D. J. Koga, and J. K. Eaton, "An Experimental Investigation of the Flow Between Shrouded Corotating Disks," Rept. MD-50, Dept. of Mechanical Engineering, Stanford University, April 1988.
10. Pauley, W. R., and J. K. Eaton, "The Fluid Dynamics and Heat Transfer Effects of Streamwise Vortices Embedded in a Turbulent Boundary Layer," Rept. MD-51, Dept. of Mechanical Engineering, Stanford University, August 1988.

Published Discussions:

Johnston, J. P., and J. K. Eaton, Discussion "On Vortex Wind Power," Trans. ASME, J. Fluids Engineering, 100, No. 2, pp. 252-253, June 1978.

Eaton, J. K., and J. P. Johnston, Discussion of "Turbulent Flow over a Plane Symmetric Sudden Expansion," Trans. ASME J. Fluids Engineering, 101, p. 532, December 1979.

Rogers, C. R., S. R. Kale, and J. K. Eaton, Discussion of "Laser-Doppler Measurements of Flow in Freeboard of a Fluidized Bed," AIChE J., 1984.

Presentations at Meetings and Symposia:

Nordquist, J. S., and J. K. Eaton, "The Effect of Varying Cooling Flow Rate on the Flow in a Simplified Turbine Disk Cavity," Bull. American Phys. Soc., Vol. 31, 1741, November 1986.

Eaton, J. K., "Physical and Numerical Experiments on the Interaction of Particles with Turbulence," Euromech 220, Cambridge, March 1987.

Moffat, R. J., P. Maciejewski, J. K. Eaton, and W. R. Pauley, "Heat Transfer with Very High Free-Stream Turbulence and Streamwise Vortices," Turbine Engine Hot Section Technology 1986, NASA Conference, Publication 2444.

Squires, K. D., and J. K. Eaton, "Numerical Experiments in Solid Particle Dispersion," Bull. Amer. Phys. Soc., Vol. 32, p. 2035, November 1987.

Pauley, W. R., and J. K. Eaton, "Transport of Streamwise Vorticity in Boundary Layers with Longitudinal Vortex Pairs," Bull. Amer. Phys. Soc., Vol. 32, November 1987, p. 2037.

Nelson, C. F., D. J. Koga, , and J. K. Eaton, "Phase-Averaged Measurements of the Unsteady Separated Flow Behind A Oscillating Flap," Bull. Amer. Phys. Soc., Vol. 32, November 1987, p. 2050.

Abrahamson, S., and J. K. Eaton, "Steady and Unsteady Boundary Layers in Rotating Disk Flow," Bull. Amer. Phys. Soc., Vol. 32, November 1987, p. 2090.

Eibeck, P. A., and J. K. Eaton, "The Effects of Longitudinal Vortices Embedded in a Turbulent Boundary Layer on Momentum and Thermal Transport," Bull. Amer. Phys. Soc., Vol. 30, November 1985, p. 1723.

Anderson, S. D., and J. K. Eaton, "Plane of Symmetry Flow in a Complex Three-Dimensional Turbulent Boundary Layer," Bull. Amer. Phys. Soc., Vol. 30, November 1985, p. 1752.

Eaton, J. K., and A. R. Feild, "Flow Visualization Study in a Modelled Computer Disk Drive," Bull. Amer. Phys. Soc., Vol. 28, November 1983, p. 1366.

Cutler, A. D., and J. K. Eaton, "Conditionally Sampled Velocity Measurements in an Unsteady Diffuser Flow," Bull. Amer. Phys. Soc., Vol. 26, November 1981, p. 1262.

Eaton, J. K., and J. P. Johnston, "Structure in a Reattaching Turbulent Shear Layer," Bull. Amer. Phys. Soc., Vol. 25, November 1980, p. 1070.

Eaton, J. K., J. P. Johnston, and A. H. Jeans, "Measurements in a Reattaching Turbulent Shear Layer," Bull. Amer. Phys. Soc., Vol. 23, October 1978, p. 1009.

Eaton, J. K., "The Interaction of Particles and Turbulence," NSF Fluid Dynamics and Hydraulics Program Review, May 1988.

Eaton, J. K., "Flow Visualization Studies of Disk Drive: Dominant Structures and Implications for Numerical Modelling," CDC Workshop on Numerical Modelling in Disk Drives, May 1988.

Invited Seminars: (Past Two Years)

Department of Mechanical Engineering, University of California,
Berkeley
Department of Aeronautics, Imperial College of Science and Technology,
London, England
Department of Aeronautics, Queens College, University of London,
London, England
Department of Mechanical Engineering, University of Surrey,
England
Engineering Department, Cambridge University, England
University of Karlsruhe, Karlsruhe, F.R.G.
University of Lausanne, Lausanne, Switzerland
Technical University of Berlin, Berlin F.R.G.
Control Data Corporation
University of Southern California
California Institute of Technology
Memorex Corporation
IBM-Almaden Research Center
Storage Technology Corporation
Garrett Turbine Engine Company
General Motors Research Laboratory
Science University of Tokyo
Electric Power Research Institute
University of Arizona