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LEVEL II

EFFECT OF MODIFICATION OF THE TRAILING EDGE OF A SEPARATING WALL ON THE DOWNSTREAM MIXING OF PARALLEL FLOWING STREAMS

THESIS

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Captain USAF

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EFFECT OF MODIFICATION OF THE TRAILING EDGE OF A SEPARATING WALL ON THE DOWNSTREAM MIXING OF PARALLEL FLOWING STREAMS

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

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Graduate Engineering Aeronautics

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Preface

This thesis represents my efforts to establish a useable low speed wind tunnel facility in which the mixing of parallel streams of air may be studied at the Air Force Institute of Technology. I hope that this investigation will provide incentive for others to study aerodynamics with this apparatus.

I wish to express my appreciation to Dr. William C. Elrod for his inspiration during this study. Major John Vonada and Captain Michael Kirchner also deserve my thanks, along with Mr. William W. Baker and Mr. Howard L. Cannon. Finally, I wish to express my gratitude to my wife, Catherine, for her devotion and understanding during this endeavor.

Daniel J. Gurecki

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Abstract

The objective of this thesis is to study ways to enhance the mixing of two parallel streams of air by modifying the trailing edge of a separating plate. An apparatus was designed which achieved two-dimensional, uniform flow near the center of the test section passage. A single element hot film probe was used to acquire data. The probe was oriented parallel to the plate trailing edge. The turbulence intensity, based on the fluctuating velocity components perpendicular to the hot film, ranged from 2.2 percent in the freestream, to 38 percent in the plate wake. Measurements of the wake were made by varying the velocity ratio of the secondary to primary stream from 1.0 to 0.375. Data was taken in and upstream of the asymptotic region. A simple flat plate and a flat plate for which the trailing edge was slotted with five, eight millimeter slots were investigated. The ratio of slot width to plate overall width was 0.157.

The flat plate wake was found to have better mixing than when modified with slots. The flat plate wake had higher turbulence and greater width than the slotted plate wake. No velocity ratio of the two streams was found to maximize the wake growth for either configuration. Wake growth doubled when the secondary velocity was 40% of the primary velocity as compared to the wake growth for equal velocity streams.

I. INTRODUCTION

In many systems it is desirable to mix parallel, co-flowing gas streams in the shortest practical distance. It occurs in aircraft turbofan engine designs that combine the core flow with the bypass flow to permit exhausting the entire mass flow through a single nozzle. Significant increases in performance can be obtained when these mixers are properly designed. Blackmore and Thompson (Ref 3:1) use an advanced, three-dimensional, viscous computer program to solve the design of a turbofan lobed mixer. They report that the mixer increases efficiency and lowers thrust specific fuel consumption by 3 to 5 percent at cruise. Another current engineering problem is to promote mixing of hot and cold streams to provide a change of stream temperature to meet a particular need. An example is the reduction of engine exhaust plume temperature profile to reduce its detectability.

Dr. Arthur J. Wennerstrom, Chief of the Compressor Research Group, AFWAL/PO, is the sponsor of this work. His work suggests that slotting the trailing edge of the last stage bladerow of an axial flow compressor could diffuse the blade wakes and increase mixing in the combustor (see Figure 1).

As a first step in this area of research, a flat plate was selected. Modifications to its trailing edge could be studied in an effort to enhance mixing.

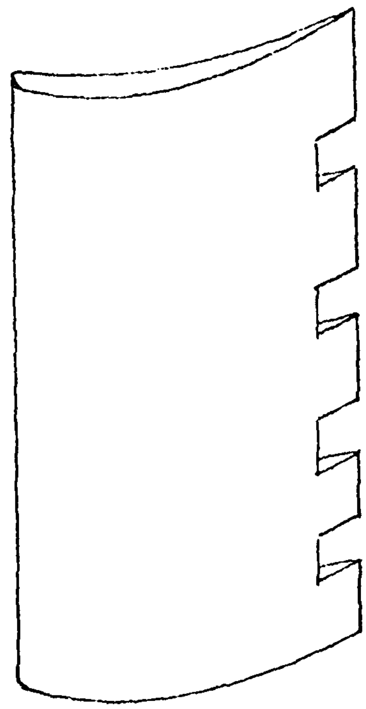


Fig. 1 Trailing Edge Crenelations Applied to an Axial Compressor Stator

Purpose and Scope

The purpose of this work is to investigate modifications to the trailing edge of a wall separating two co-flowing, parallel streams of gas. The modifications are intended to increase the mixing of the two streams by the use of slots.

Turbulent wakes are chosen as the subject of this study due to their high mixing characteristics. In order to limit the complexity of the apparatus, the parallel streams are chosen to be incompressible, and two-dimensional airflows. Since the streams are of the same total temperature, heat transfer will be neglected. The temperature and pressure of the air are such that the flow behaves as an ideal gas.

An existing calming chamber will be used to provide a common source for the parallel flows. Devices that establish resistance to the flow will be provided in the respective streams as needed to establish the desired velocity ratios. The apparatus will be checked for uniform, non-separated flow of uniform turbulence level in the freestream. A flat plate separating wall will be tested to determine the extent of the wake growth and its interaction with the apparatus wall boundary layers. Data from the flat plate wake will be compared with empirical and theoretical work of others to evaluate the quality of the flow and establish a base line case for comparison with the wakes of subsequent trailing edge modifications. Finally, a modification to the flat plate will be tested, which consists of five, eight millimeter slots cut into the trailing edge. The data of both plates will be analyzed to determine which configuration achieves the better mixing.

II. THEORY

This chapter summarizes pertinent knowledge found in the literature and shows how these facts relate to the enhancement of mixing of two parallel streams of air. A general definition of turbulence is given, followed by those characteristics which lend themselves to good mixing. Ways to measure turbulence are then surveyed, followed by a discussion of flat plate wakes.

Cebeci and Smith define turbulence in part with a quote from Hinze:

> Turbulent fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned (Ref 7:3).

Turbulence is a three-dimensional phenomenon, in which diffusion of flow properties occurs much more rapidly than in laminar flow (Ref 7:26). The velocity components of turbulent flow can be decomposed into time average and fluctuating components. Since mass is transferred across the mixing layer by the fluctuating velocity component transverse to the wake, any increase in the transverse velocity fluctuation causes more complete mixing to occur (Ref 1:53,55).

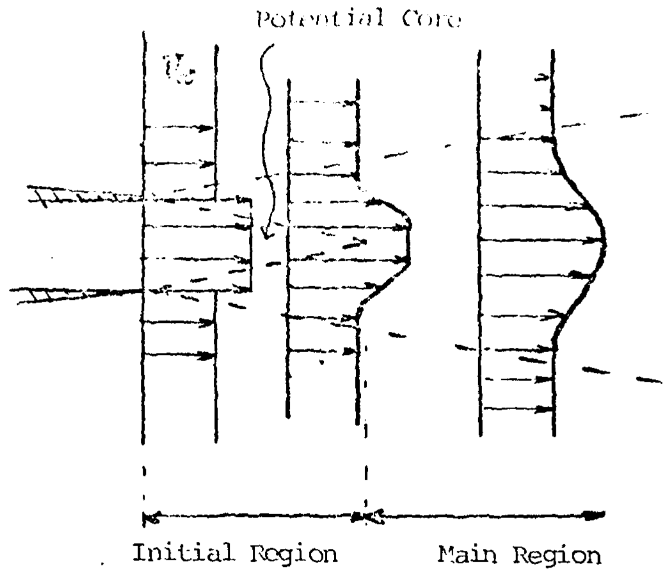
Cebeci and Smith report that the downstream response of a turbulent boundary layer to an obstacle in its path is more rapid than the response of a laminar boundary layer. They cite the work of Klebanoff and Diehl which shows that the turbulent boundary layer returns to an undisturbed state quicker than the laminar boundary layer due to the high diffusion of the turbulence (Ref 7:92).

In turbulence, velocity fluctuations interact over many scales of time and length to produce mixing. The smallest eddies do not contribute much to overall mixing, and eventually dissipate as heat energy due to viscous shear. The largest eddies contribute most to the transport of properties in the wake, but eventually, they break down into smaller eddies. Schlicting points out that, from empirical data, turbulence in subsonic flows mixes flow properties more completely than in supersonic flows (Ref 13:739). The subsonic turbulent wake offers the most thorough mixing.

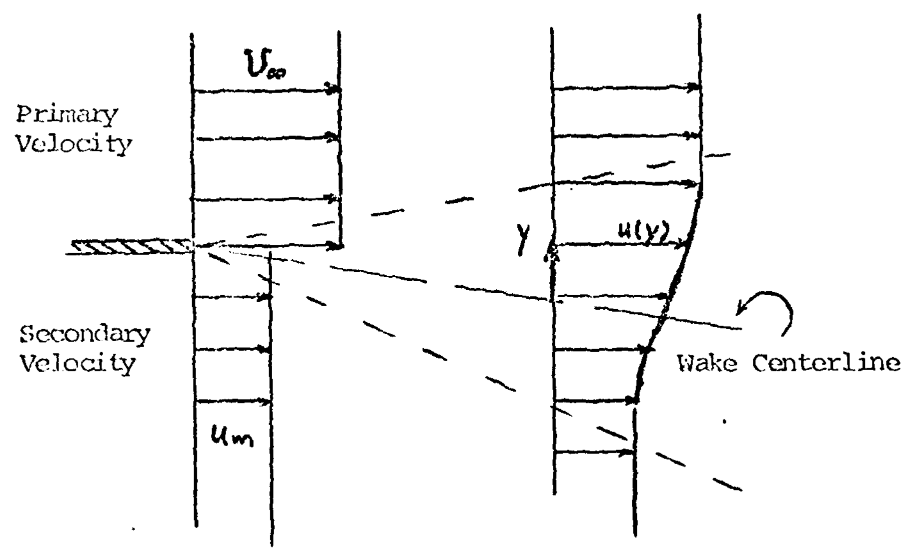
The motion of turbulent eddies adjacent to a non-turbulent flow entrains the freestream into the wake. Thus the wake diffuses into the surrounding flow. Browand explains this action in terms of vortex pairing in his study of two parallel flows mixing behind a splitter plate (Ref 5:129). Brown, studying the mixing layer of a plane turbulent jet, shows that the slower flow is entrained by the faster flow. The rate of entrainment is shown to be weakly dependent on the relative densities of the flows, and strongly a function of the difference in the flow velocities (Ref 6:38). Entrainment in the mixing region directly affects the growth of the wake.

In a wake behind a body of appreciable thickness, the turbulence develops a nearly constant character with time and distance, following a region of wake development. The region of development is called the transition region and the developed region is called the asymptotic or self-preservation region. The asymptotic region is identified by its behavior according to a similarity law: velocity profiles at different downstream locations can be non-dimensionalized as a single curve. Turbulence intensity also obeys a similar similarity law. Turbulent wakes have a universal behavior which is independent of the body shape in the asymptotic region (Ref 9:1388). For wakes of circular cylinders, mean velocity profiles show that similarity exists beyond about 80 cylinder diameters downstream. Turbulence intensities do not become similar until 200 diameters (Ref 15:113).

Figure 2a shows a uniform plane jet exhausting into a region of uniform, slower flow. As the jet interacts with the slower flow, shear layers grow between the flows. The initial region of the jet is defined as the region where the potential core of the jet exists. The main region of the jet occurs downstream of the initial region. Experiments have shown that in the initial as well as the main region, velocity profiles exhibit similarity. Due to the symmetry of the plane jet, the shear layer of two flows of different velocities, mixing downstream of a thin separating wall (Figure 2b) exhibits the same



a) Jet in Uniform Flow (Ref 1:4)



b) Wake of a Thin Flat Plate (Ref 1:173)

Fig. 2 Mixing Region Schematics

similarity as the velocity profiles in the mixing layers of a plane jet (Ref 1:4-10). Because the shearing forces from the difference in the two velocities promote additional mixing in the wake of the separating wall, the mixing region of either a plane jet or a flat plate depends strongly on the velocity differential across the mixing region

Characteristics of Good Mixers

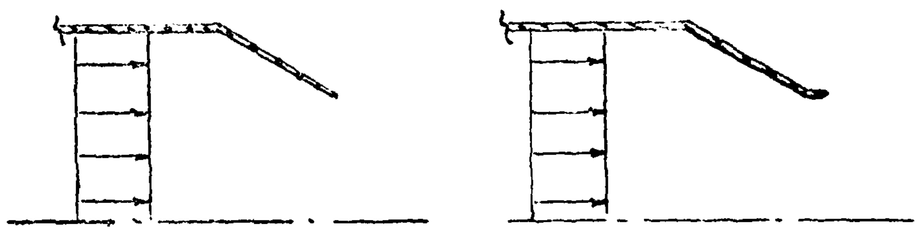
In the design of mixers for turbo-fan jet engines (see Figure 3), it has been found that a smoothly flaired lip at the exit of the by-pass duct passes more flow and increases efficiency of the mixer (Ref 16:26). In the design of any bends of the separating wall of the two streams, this fact must be considered. A large region of separation due to an abrupt bend would increase losses in the flow.

Stratford, Jawor, and Smith investigated the mixing of two streams of air in a centrifugal flow field. The flows were found to mix better when the fluid of higher total pressure was centrifuged through the fluid of lower total pressure (Ref 14:12) The extent of mixing was measured by the width of the mixing region (Ref 14:11).

The effect of mixing fluids of different densities was not considered in this thesis, but the extent of mixing was assumed to be directly proportional to the width of the mixing region.

Turbulence Measurement

Turbulence has been characterized in many ways including its intensity, length scales such as the Taylor and the



a) Convergent Nozzle b) Flaired Lip Nozzle

Fig. 3 Convergent Nozzle and Flaired Lip Nozzle (Ref 13:13,28)

Kolmogorov scales, the power spectral density of the eddies, the Reynolds shear stress components and temporal and spatial correlations of the above (Ref 7:13-24). Of the many ways to measure turbulence, one of the most basic is the use of a single element hot wire probe, which was used in this study.

Research on Flat Plate Wakes

Many researchers have studied the wake of a flat plate and the findings are well established. Agrawal, Pande, and Prakash studied the near wake of a flat plate at zero angle of attack. Velocity defect was measured across the wake and at several downstream stations. Turbulence intensity was plotted versus vertical distance across the wake, made dimensionless by dividing by the trailing edge displacement thickness. Velocity defect was plotted in the asymptotic region. A single element hot wire probe was used (Ref 2:140). Similar studies were also found in references 8 and 9.

Abramovich summarizes the work of several researchers with dimensionless plots of velocity defect for a two-dimensional, incompressible wake of a flat plate. Data is shown in the asymptotic region for streams of equal and unequal velocities (Ref 1:28,29,140). This empirical data agrees with the Law of Decay of the Velocity Defect (Ref 1:133-139). It is expressed in the following equation:

$$\frac{U_\infty - u}{U_\infty - u_m} = f(\eta) = (1-\eta^{3/2})^2$$

For the wake of two parallel streams of equal velocity, the local dimensionless velocity deficit is a function only of η, the coordinate measured across the wake width divided by the wake half width (see Figure 2b). This theory is also modified to account for cases where the velocities of the streams are not equal. Data in this study was compared to this theory whenever possible.

Ways to Enhance Mixing

It is a well-known fact that vortex generators in a flow generate turbulence, and that flaps on an airfoil create large mixing regions downstream. Vortex generators have been used in various ways to enhance mixing. Schlicting reports that for a triangular body with its vertex pointed upstream, when a splitter plate is located behind the body in the recirculation region, and oriented parallel to the flow, the wake grows at twice the rate as that of a flat plate placed perpendicular to the flow. The von Karman vortex street is inhibited by the plate, and so the wake becomes unusually wide (Ref 13:739). Vortices of opposite rotation have been created in a dump combustor to speed the mixing of fuel and air (Ref 12:i).

Turbulence needs continuous supply of energy to fuel the deformation work done by the viscous shear stresses (Ref 15:3). Therefore, to enhance the mixing in a flat plate wake, modifications must increase the energy supplied to the shear stresses. Methods of producing a larger or energized shear layer might include bending, crinkling, or slotting the plate trailing edge. Bending diverts the flow in different directions creating shear layers having different orientations in the wake. Small jets of air blowing into the main flow would energize the boundary layer to increase turbulence. Of the modifications considered, the slotted flat plate was chosen as the first modification because, if it increases mixing, it would do so with little penalty of drag.

The mathematics of turbulent flows are complex and solutions are not generally known.

> Since the equations of motion are non-linear, each individual flow pattern has certain unique characteristics that are associated with its initial boundary conditions. No general solution to problems in turbulent flow are available (Ref 15:3).

Solutions to turbulent mixing flows must be studied by the analogy of experiment.

III. APPARATUS AND PROCEDURES

The purpose of this chapter is to give a description of the equipment, how it was used to obtain the data, and in general, what data was taken. Following the sections on apparatus design, data acquisition, and data reduction, the apparatus preliminary checkout is discussed.

Apparatus Design

An experimental apparatus was designed to achieve two parallel streams of gas, separated by a flat plate, which were allowed to mix in the wake of the plate. The wake was to be turbulent and the flows were to be of uniform freestream velocity and turbulence intensity.

The working fluid was chosen to be air. Optical glass walls were used as the sidewalls of the test section to permit visualization of the flow with smoke, tufts, or by means of a Schlieren optical system. Air, supplied by the AFIT facility compressor at 100 psi and room temperature, was used.

Velocity of the flow was chosen in the incompressible range. Design velocity at the flat plate trailing edge was 300 ft/sec, roughly a Mach Number of 0.3. The pressure differential needed to exhaust the flow to this velocity was calculated to be 0.751 psi from the incompressible Bernoulli Equation. Test section flow area was based on the compressor discharge capability of 1.0 lbm/sec, using conservation of mass at steady state. Density was calculated from the ideal gas equation of state. The area required to pass the total available supply of air at design velocity was 6.21 in^2. An area of 4.0 in^2 was conservatively chosen for the design.

The length of the plate was based on Reynolds number considerations. For a turbulent boundary layer, the Reynolds number at the lower end of the turbulent flow regime is 3.2×10^5, from Schlicting (Ref 13:37), Boldman, Brinich and Goldman designed a similar apparatus and cited a limiting Reynolds number for turbulent flow as 10^5 (Ref 4:724). Using Schlicting's limit the minimum length of the plate was found to be about 2.0 inches. For a reduction of velocity of 33%, as anticipated in the experiments, the minimum length triples, so 6.0 in was chosen for the flat plate length.

The apparatus is shown in Figure 4. Hardware included the conical diffuser, the filter paper and perforated plate, the adaptor to the square calming chamber, the calming chamber itself, and one straight-walled convergent section. The square cross section stilling chamber used three internal flow screens to mix the flow. The hot film anemometer was chosen as the primary form of instrumentation. The life of the sensor is directly related to particulate matter carried by the flow field. Four paper filters were used to eliminate dust at the entrance to the chamber. Since the velocity of one stream had to be made more variable, separate calming chambers for each air stream were initially considered. A simpler design was possible using one common calming chamber with a total pressure loss imposed on the secondary flow stream with various cloths to obtain various velocity ratios as needed.

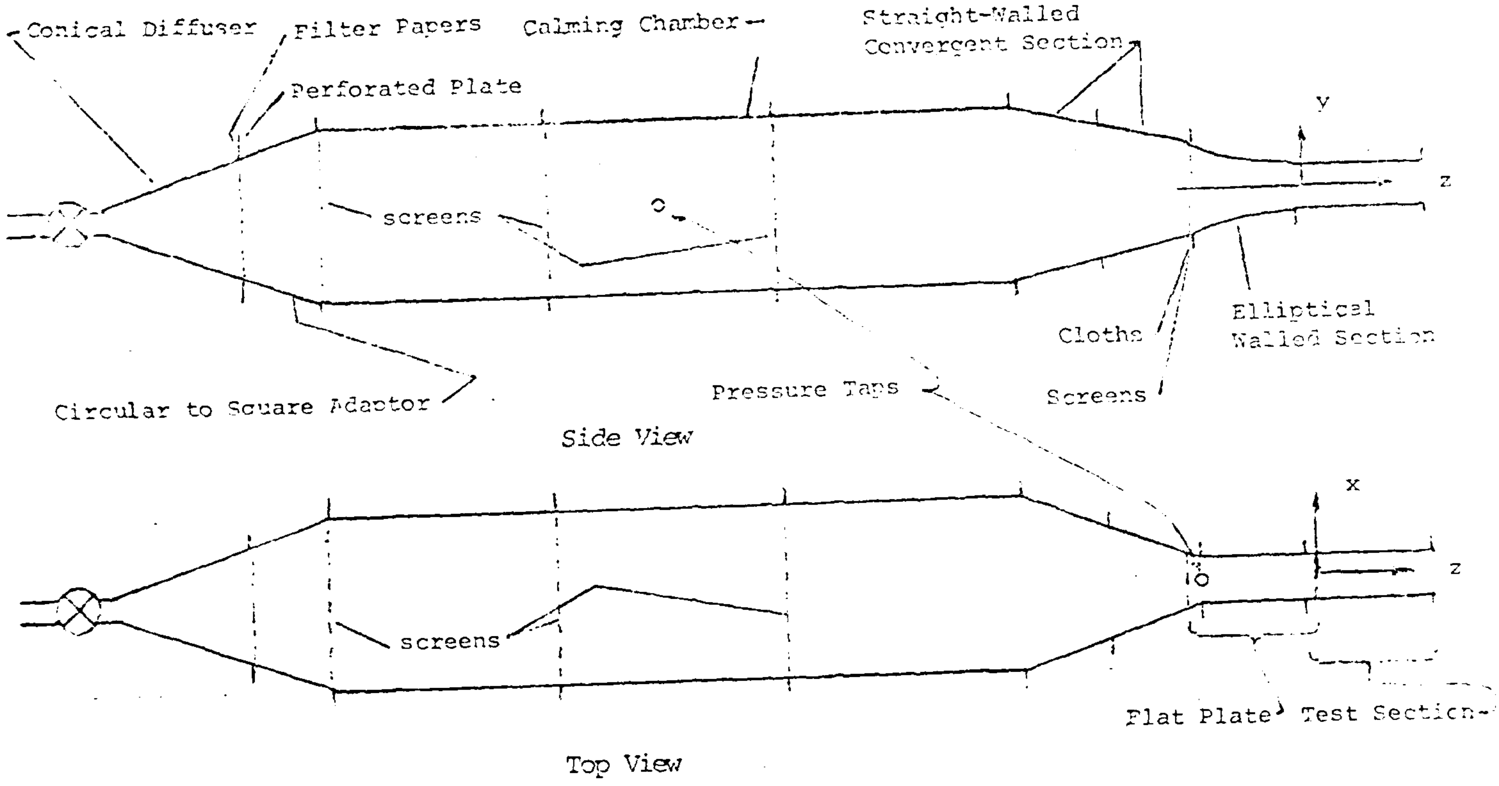


Fig. 4 Apparatus

To test different modifications, the flat plate, held by friction, was made to slide in slots in the walls immediately upstream of the test section (see Figure 5). This requirement dictated that a section of constant width enclosed the plate. The cloths also had to be replaceable to obtain different velocities, and were not mounted at the plate leading edge because the crossflow potential which they would produce there was expected to contribute to non-uniform flow in the test section. The cloths were mounted one inch downstream of the leading edge, dividing the plate into two parts which butted together at the screen and cloths.

At this juncture, the sidewall surface had a sharp corner. A 1/8 in rubber gasket was installed which located the screen and cloths 1/8 in downstream of the corner. Any separation of the wall boundary layer at the corner was intended to be adequately diffused throughout the flow downstream of the screen.

On the downstream side of the screen, the height of the channel had yet to be reduced to that of the test section. A straight-walled convergent section between the last screen and the test section would have resulted in a sharp angle at the juncture to the test section, possibly separating the flow along the upper and lower test section walls. Elliptic walls were used to gradually reduce the channel height and provide parallel flow at the test section entrance.

In the design the calmed flow passed through the existing straight-walled convergent section. Another straight walled

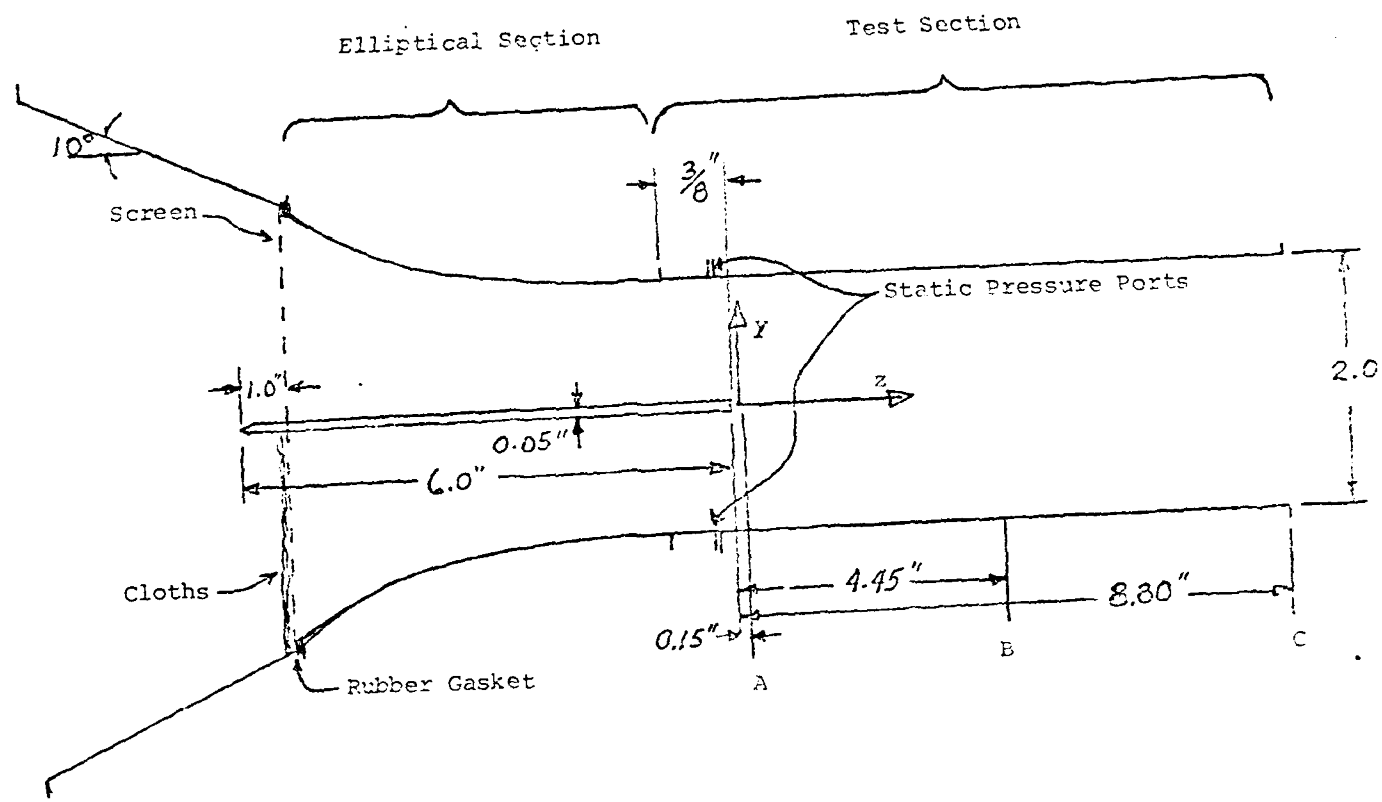


Fig. 5 Detail of the Plate and Test Section

convergent section was designed, preserving the wall angles of the existing hardware. Its exit width was that of the test section, 5.1 cm. Height reduction was achieved by a section having elliptical top and bottom walls as recommended in the literature (Ref 10:46). The trailing edge of the plate was made to protrude into the glass-walled, test section for visual positioning of the probe and possible optical investigations. The plate was made of aluminum stock, 0.050 in thick, and the ratio of the test section area to the calming chamber area was 0.033.

Data Acquisition

The single element hot film anemometer system was used to measure the flow velocity. The DC and RMS voltages were measured, then interpolated on the calibration curve to get the mean and fluctuating velocities. The hot film was not rotated in the flow.

The instrumentation consisted of:

1. TSI Model 1050, constant temperature anemometer
2. TSI Model L266 and K478 sensors; each film was 0.0020 in thick
3. Ballantine Laboratories Model 320A, True RMS VTVM
4. Hewlett Packard Model 34701A, D.C. digital voltmeter

The probe was mounted in a Gaertner Scientific Company floor standing traverser, Model 1021. As an aid in preliminary checkout, static pressure ports were installed above and below the training edge of the flat plate. A pressure line was connected to the wall of the stilling chamber to indicate total pressure. Pressure lines were connected to water manometers.

The procedure of testing was as follows:

1. The electronics were turned on and the ambient temperature and pressure were recorded.

2. The hot film was aligned parallel to the flat plate trailing edge.

3. The electronics were considered warmed up when the STAND-BY output of the hot film remained 2.0 volts within 0.005 volts over five minutes duration. At this time, the apparatus was run up to a total pressure of 22 in of water, with the probe out of the airstream to blow out any foreign matter. This pressure gave approximate design conditions in the test section.

4. With the film oriented parallel to the plate trailing edge, the probe was manually positioned and data were recorded.

Whenever fluctuating values were read, an estimated average was taken. Every half hour the anemometer was adjusted back to the STAND-BY condition. The probe was calibrated four times during the research. Maximum deviations from previous calibrations were within three percent error in velocity. Appendix A discusses the calibration technique.

Traverses were taken at three distances from the plate trailing edge: location A was 0.15 in downstream; B, 4.45 in, and C, 8.80 in. Location C was 1/8 in from the exit plane of the apparatus, as shown in Figure 5.

Figures 7 through 12, discussed in detail in Chapter IV, show data taken from the flat plate wake at velocity ratios of 1.0, 0.66, and 0.375. The velocity ratio, U, is defined to be the ratio of the slower, secondary, to the faster, primary, flow velocities in the freestream at location A. Different velocity ratios were obtained by inserting cloths upstream of the last screen on one side of the plate. The same cloths were used for the slotted plate tests.

Data Reduction

The data were reduced with the aid of two computer programs which processed voltage, velocity, RMS voltage, and the data point coordinates. The output consisted of the raw data and computed dimensionless parameters for plots. The x-direction was parallel to the plate trailing edge, the y-direction was perpendicular to the x-direction and was vertical, and the z-direction was orthogonal to x and y, in the downstream direction as shown in Figure 5.

To discern the boundaries of the wake regions from the freestream, a turbulence parameter was formed, based on the assumption of a linear voltage-velocity relationship in the calibration curve, over a given range of fluctuation. The turbulence parameter was defined as the ratio of RMS to mean hot film output voltages at a data point. Usually the assumption of calibration curve linearity is valid for either linearized hot film output or for turbulence intensities of less than 0.05. Freestream intensities were calculated to be 0.02 and so the calibration curve linearity is justified for locating the outer boundaries of the wakes. Typical calibration curves are presented in the Appendix.

For the region within the wakes, the turbulence intensities reach typical values of 0.38 or more. Here, the turbulence parameter no longer indicates turbulent intensity. Turbulent parameter values are used only as a means of comparing relative levels of fluctuations within the wakes, since turbulent intensities were not calculated for each data point.

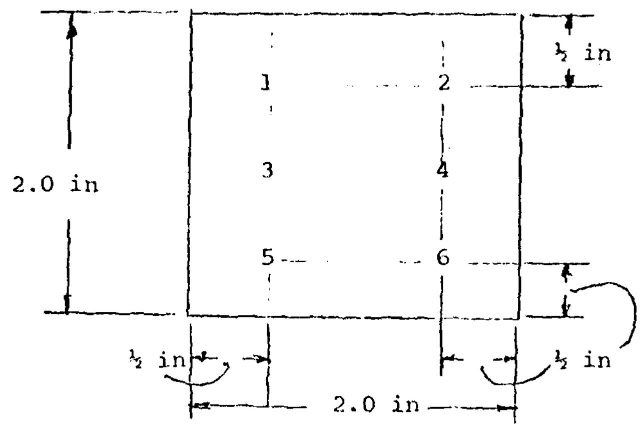
Apparatus Checkout

Uniformity of flow and freedom from boundary layer effects were of great concern in the untested apparatus. Traverses were taken at A and C to determine the flow condition and the final extent of the boundary layers and wake.

The preliminary apparatus checkout dealt with six points at each axial location. Axial locations examined were the standard A, B, and C locations, shown in Figure 5. Table 1 shows the six check points used to insure that the wall boundary layers did not effect the wake development. The uniformity of velocities and RMS values at points 1, 2, 5 and 6 indicates that the corner boundary layers are less than 0.50 in thickness. The high RMS values at points 3 and 4 show that the wake is detectable along the length of the channel. The apparatus and instrumentation functioned satisfactorily, so a detailed investigation of flow uniformity and boundary layer growth was performed and discussed in Chapter IV.

Table 1 Boundary Layer Checkpoints

Rear View of Test Section:



Point	Velocity at A Average	Fluctuating	at B Ave.	Fluct.	at C Ave.	Fluct.
1	271.0	9.33	274.0	9.17	282.0	10.18
2	271.0	9.33	275.0	9.33	282.0	10.18
3	235.5	52.31	247.5	20.00	261.0	15.00
4	253.0	35.71	251.0	20.64	261.3	15.00
5	275.0	9.33	276.0	9.17	282.0	10.36
6	274.8	9.17	277.0	9.17	282.8	10.46

NOTE: Velocity in f/sec.

IV. RESULTS AND DISCUSSION

This chapter will present and analyze the data and then determine if the modification to the flat plate trailing edge achieved better mixing than the flat plate itself. The velocity ratio of the two airstreams, U, is defined as the slower, or secondary, divided by the faster, or primary, freestream velocity. When U = 1.0, both streams are of equal velocity. First, the investigation of the boundary layer growth on the apparatus walls is presented. Data from the flat plate, taken at the three downstream locations within and before the asymptotic region, and at three values of velocity ratio, are compared to the two-dimensional wake theory in Abramovich. A non-uniformity in the flow is observed in the data and its effects are evaluated. Next the modification to the flat plate is described. The data from the wake of the modified plate is then analyzed, and the wakes from both plates are compared. Comparisons are made based on turbulence parameter values, velocity profiles, and turbulence parameter profiles.

Boundary Layer Investigation

An investigation of flow quality was conducted to determine the extent of boundary layer growth and flow uniformity in the test section. The passage was traversed in the x-direction, parallel to the plate trailing edge at A and C, both near the top of the passage and in the plane of the flat plate (see Figure 5). These data are plotted in Figure 6. The sidewall was located one inch from the passage

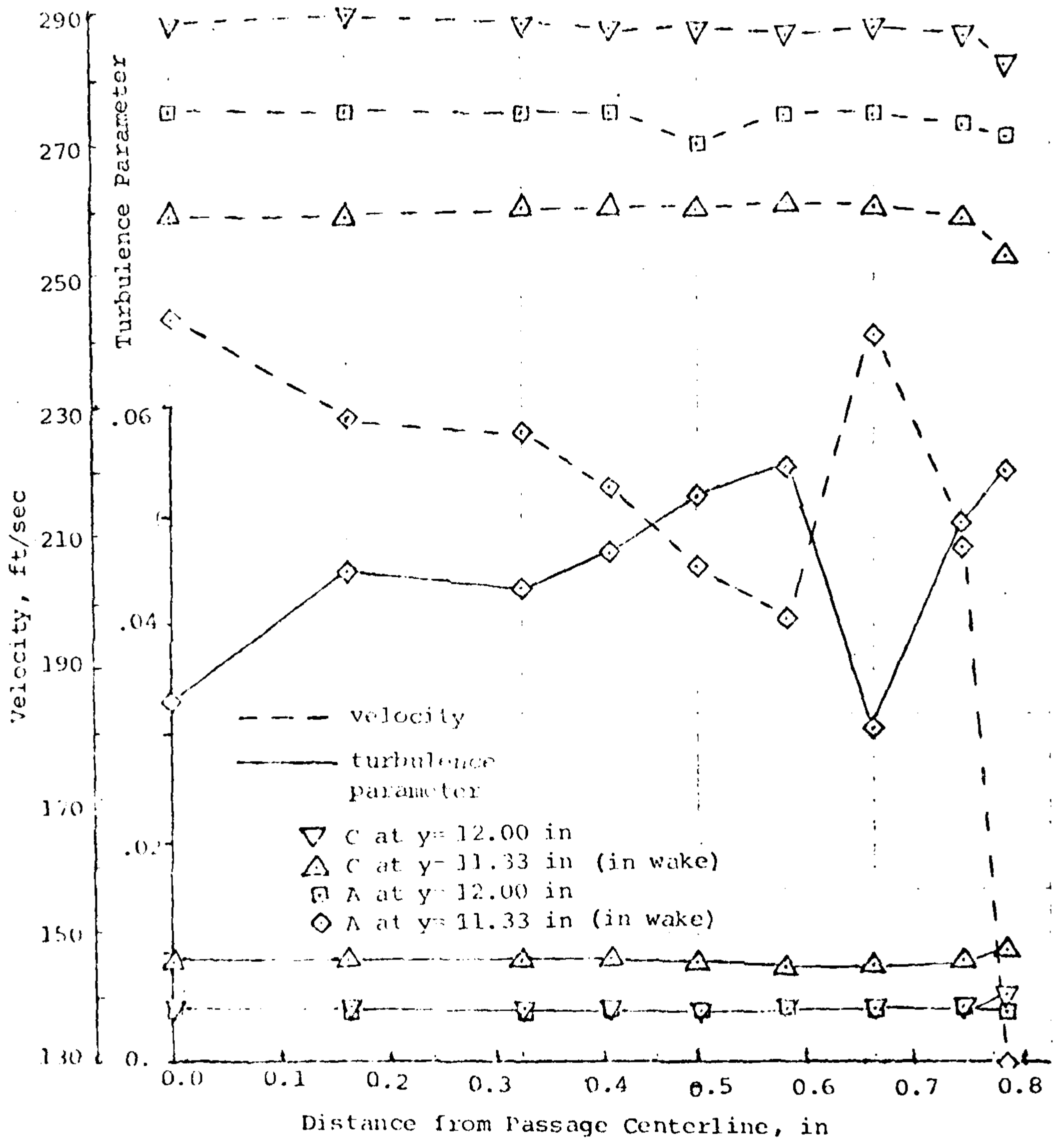


Fig.6 Lateral Traverse

Note: Sidewall located at y=1.0 in.

centerline and is not shown on the figure. The quality of the flow was uniform, except at A in the wake region. As the probe neared the sidewall, the boundary layer became evident from the simultaneous decrease in velocity and increase in turbulence parameter. At C, the wall boundary layer appeared to be 0.2 in thick on the sidewall.

From laminar boundary layer theory (Ref 13:140),

$$\delta = z5(R_e)^{-1/2}$$

where δ is the boundary layer thickness based on the downstream distance, z. The laminar boundary layer was calculated to be 0.045 in thick. From turbulent boundary layer theory (Ref 13:638),

$$\delta = 0.37z\ (R_e)^{-1/5}$$

the turbulent boundary layer was calculated to be 0.188 in thick. Both calculations used z = 8.0 in to represent the boundary layer near C, and did not account for the boundary layer thickness at the test section entrance, since it depended on the static pressure gradient in the elliptical convergent section. Since this pressure gradient was negative, the boundary layer thickness at the test section entrance was taken to be small. The boundary layer calculations above predict the order of magnitude of the boundary layer thickness. From Figure 6 at C near the upper passage wall, the boundary layer was seen to be about 0.2 in thick, which agreed with the calculated turbulent value, and not the laminar value.

Traverses were next made in the vertical, or y-direction, across the wake on the passage centerline, at A, B, and C. From the vertical traverses, Figure 7, the thickest boundary layer was about 0.2 in thick at C. Also from Figure 7, the wake thickness at C left a freestream region of about ½ in between the boundary layer and the wake. For a flat plate tested at velocity ratio of one, a margin area of freestream flow ½ in thick existed between the wake and the upper and lower wall boundary layers, so that the boundary layers did not grow into the wake in the test section.

Discussion of the Flat Plate

In examining the data from the flat plate wake, several objectives were satisfied. The wakes were found to grow with downstream distance without intersecting the wall boundary layers. The velocity profiles showed similarity downstream of a region of wake development, and this similarity was in good agreement with the two-dimensional, incompressible wake theory of Abramovich. The turbulence intensity profiles were not tested for similarity, since no similarity law was found in the literature, but the turbulence parameter in the wake did show tendency to reach a constant value with downstream distance. These points will be developed in detail in the following paragraphs. For the remainder of the discussion, only data from the vertical traverses will be discussed.

From the turbulence parameter plots, Figures 7, 8, and 9, the wake clearly widens with downstream distance, at all values of U. Maximum turbulence parameter decreases rapidly

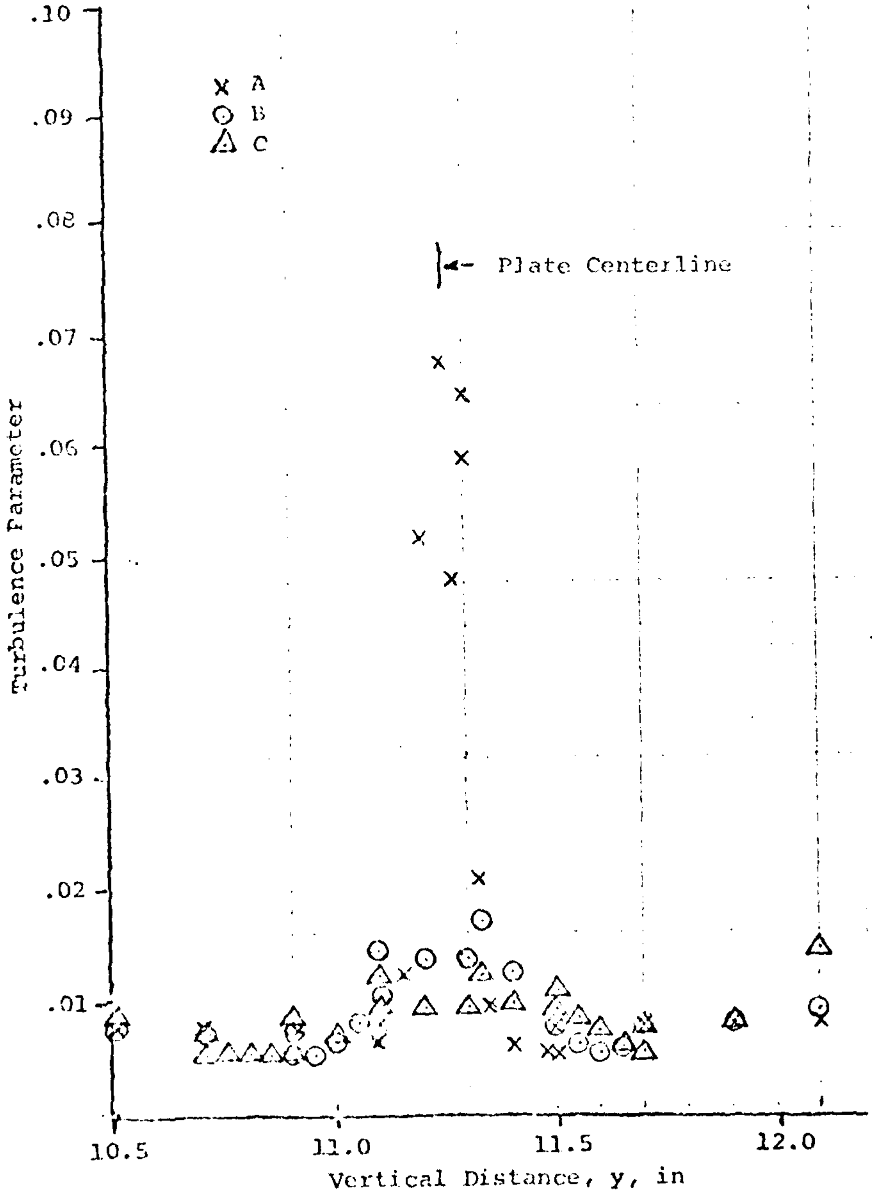


Fig. 7 Flat Plate Turbulence Parameters, U=1.0

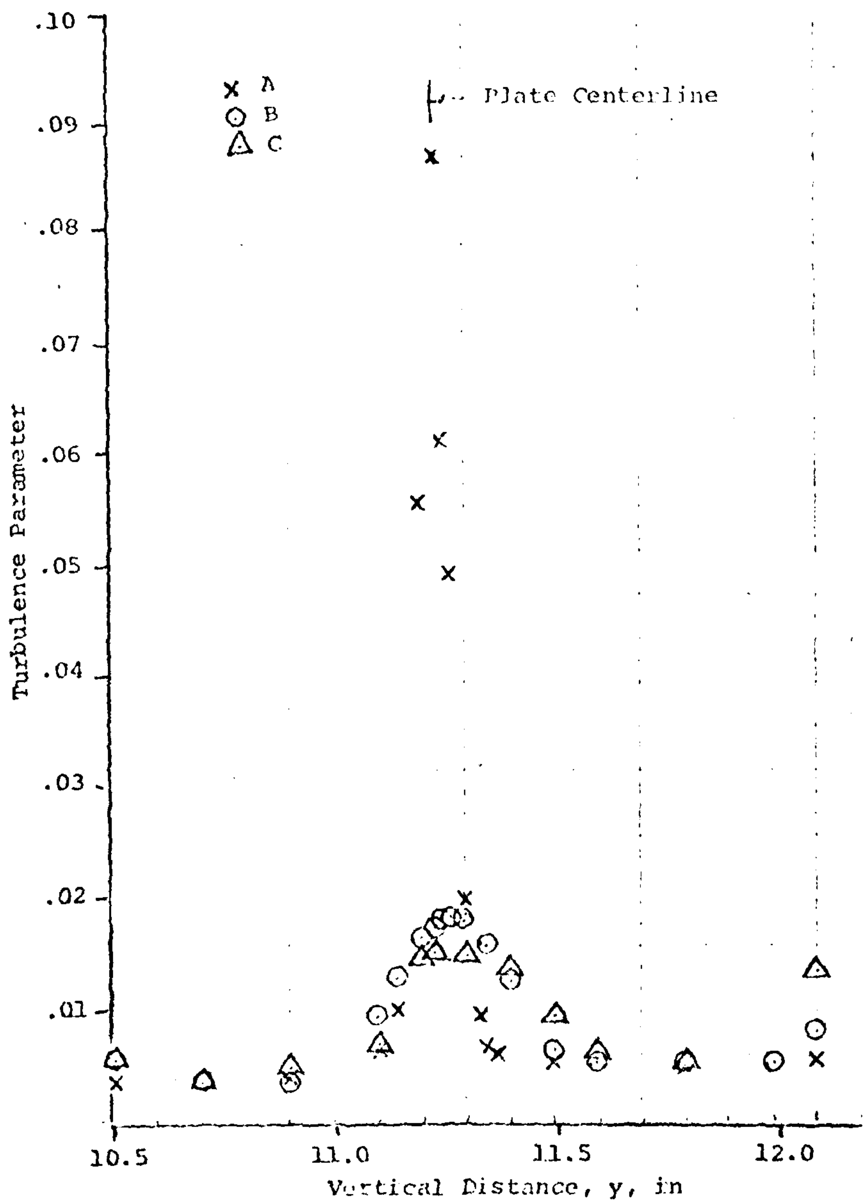


Fig. 8 Flat Plate Turbulence Parameters, U=0.66

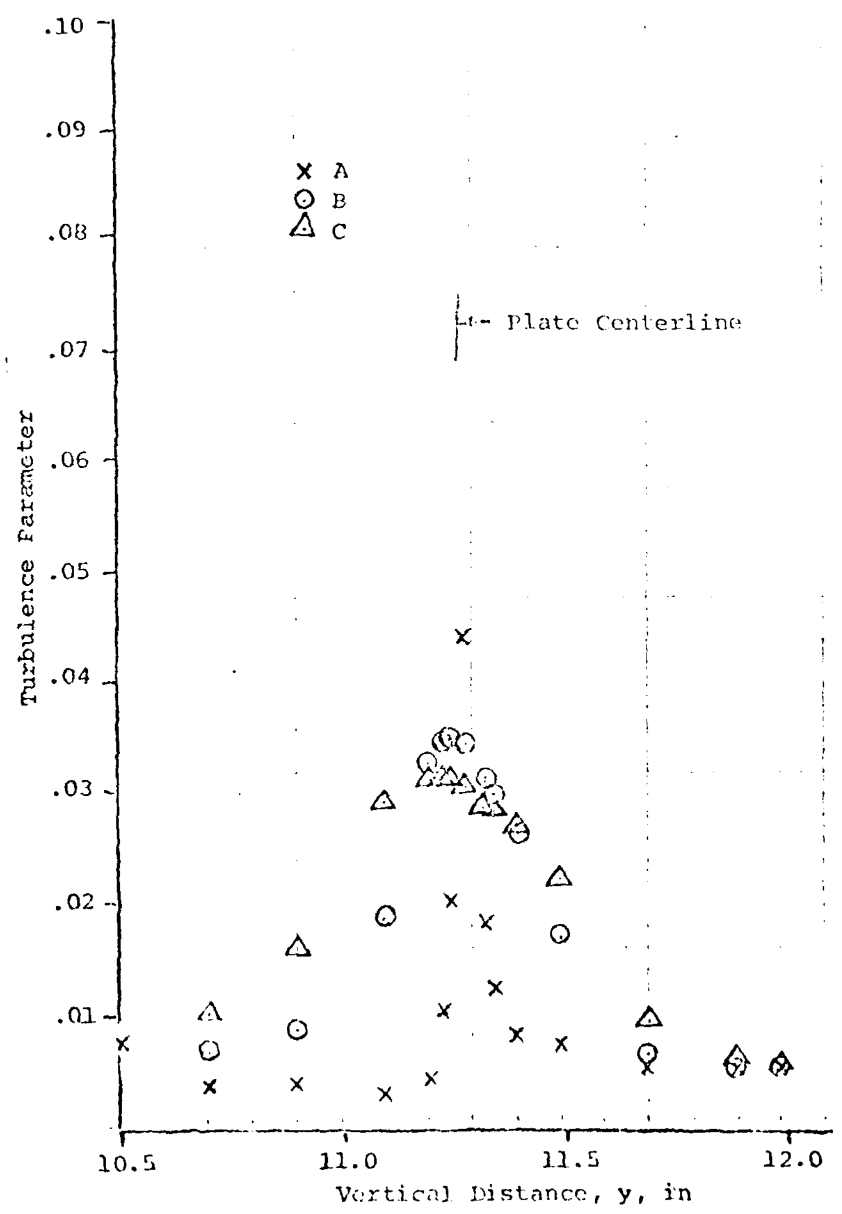


Fig. 9 Flat Plate Turbulence Parameters, U=0.375

from A to B and then more slowly from B to C. Figures 8 and 9 show the effect of decreasing the velocity of the slower stream on the asymptotic region of the wake. The peak values of the turbulent parameter, which occur in mid-wade, increase as the velocity ratio is lowered.

The velocity profiles, Figures 10 to 12, illustrate similar wake growth. As U decreases in Figures 11 and 12, the gradient of velocity across the wake diminishes and the width of the wake grows with downstream distance. In Figure 10, the point in the profile at C showing high velocity deficit on the right side of the plot is judged to be evidence of the top wall boundary layer.

In the asymptotic region of a turbulent wake, the velocity profiles are similar, when plotted as dimensionless velocity deficit versus dimensionless distance across the wake. The data was compared to the theoretical plane wake curves from Abramovich (Ref 1:140), in Figure 13, to determine to what degree the profiles were similar. The data of B and C follow the theoretical curve when U = 1.0. The data at A shows more scatter. The data of Hall and Hislop, shown in Abramovich (Ref 1:140) were taken at a downstream dimensionless distance, z/D, of 10 and 17, where z is the distance downstream of the plate trailing edge, and D is the plate thickness. In this experiment, the z/D for A was 3.0, for B, 89.0, and for C, 176.0. Figure 14 shows the measurements of the dimensionless velocity at the center of the wake plotted against z/D (Ref 9:1388). Data is shown for U = 1.0

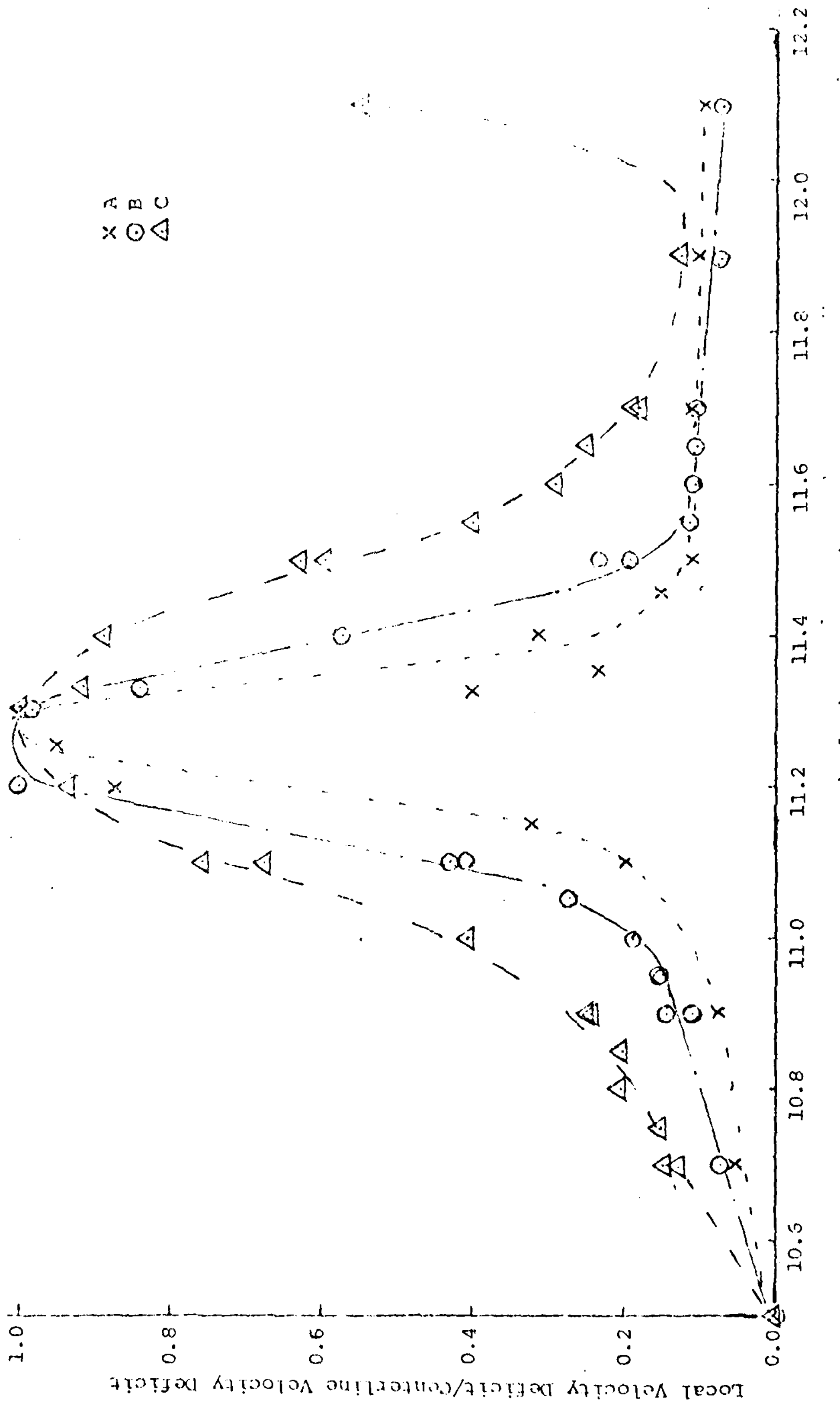


Fig. 10 Flat Plate Velocity Deficit, U=1.0

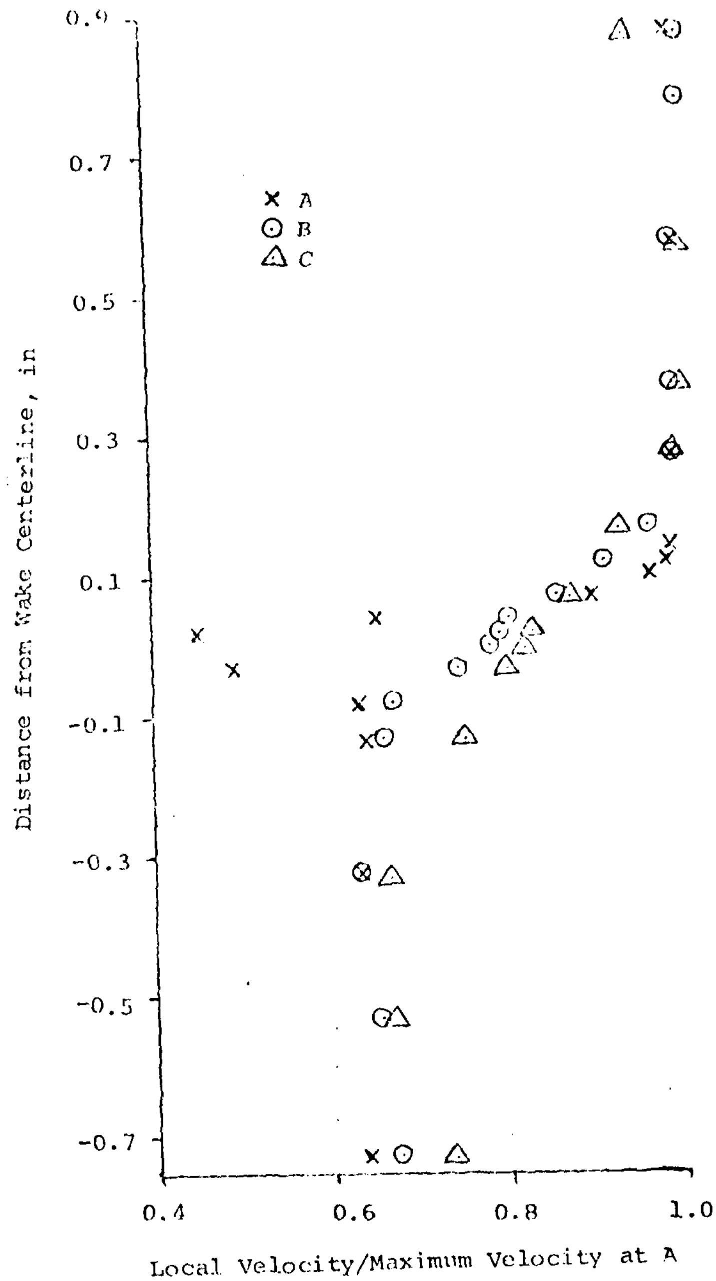


Fig. 11 Flat Plate Velocity Profiles, U=0.66

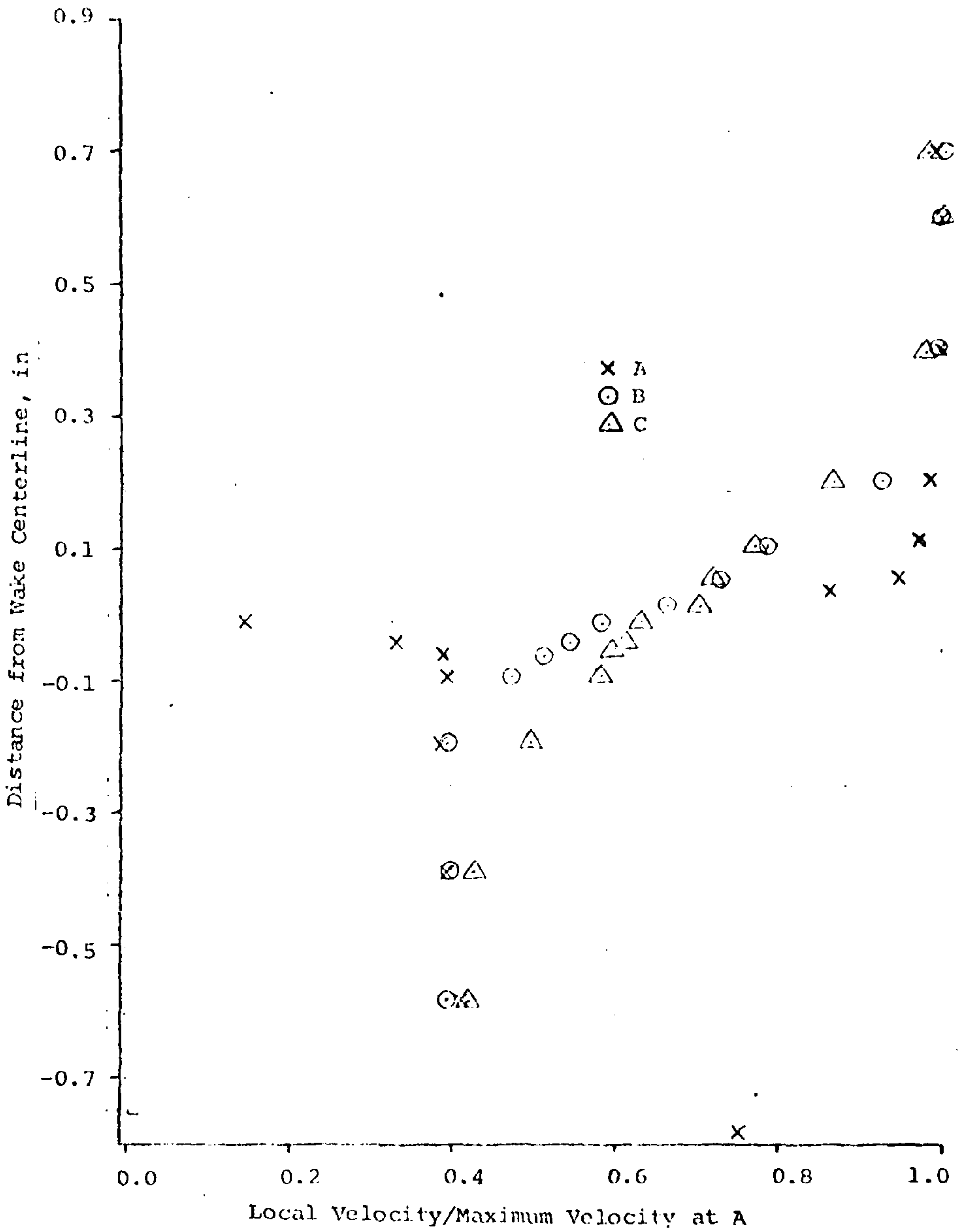


Fig. 12 Flat Plate Velocity Profiles, U=0.375

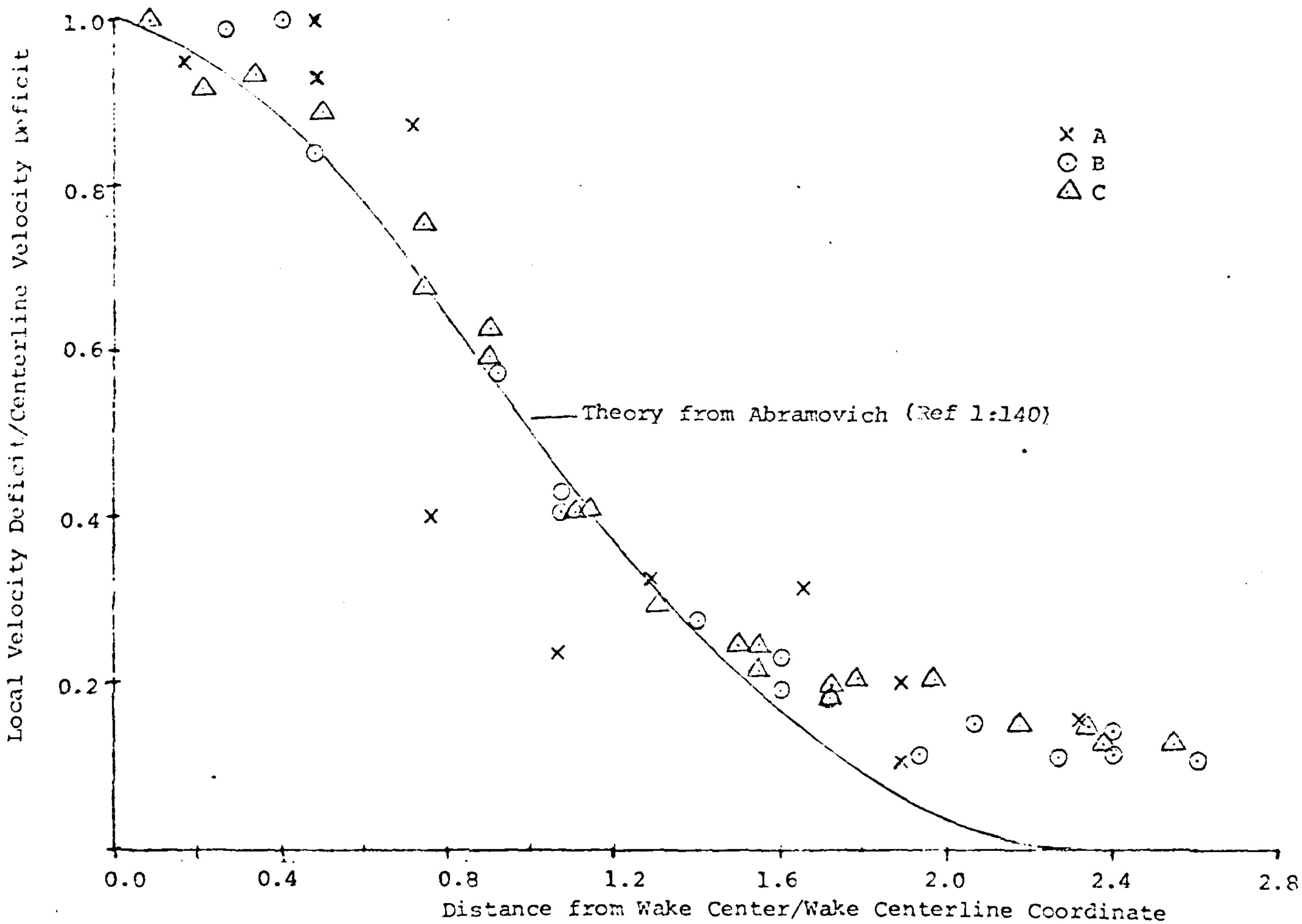


Fig. 1? Flat Plate Similarity Plot, U =1.0

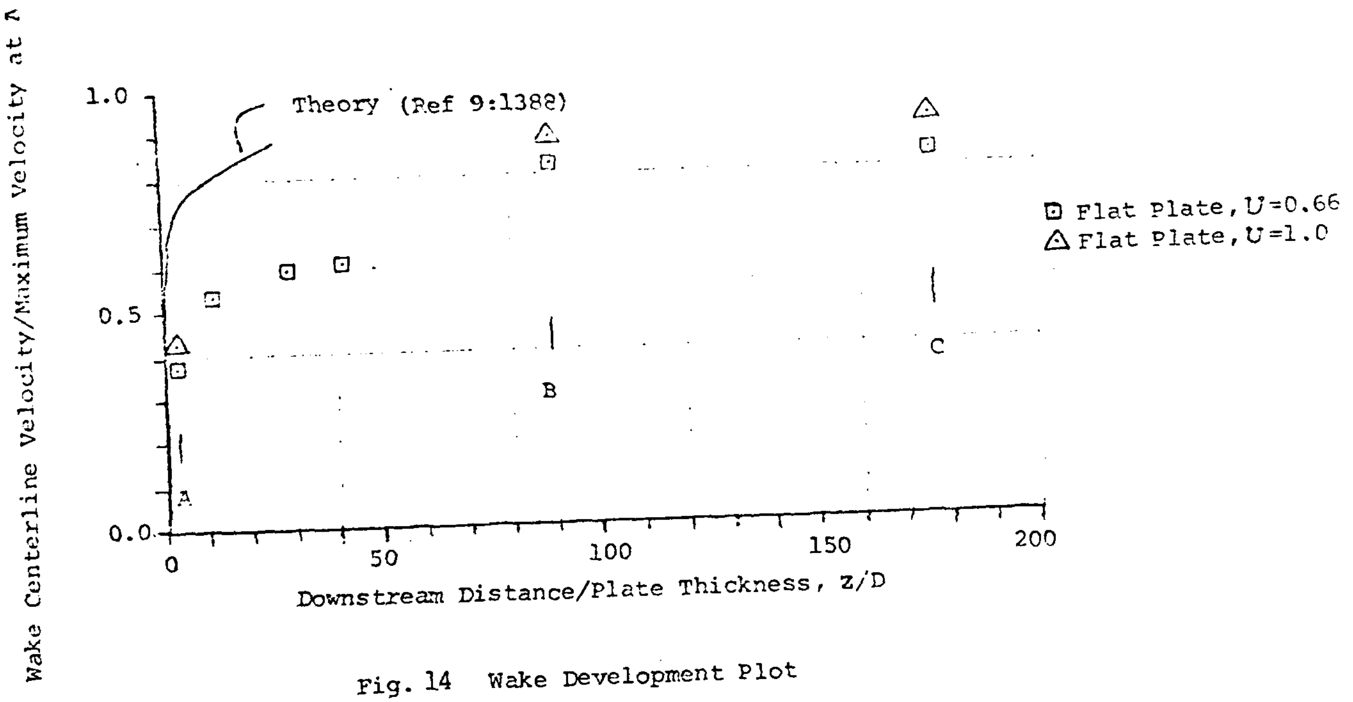


Fig. 14 Wake Development Plot

at the three locations usually examined, and for U = 0.66 at several locations between A and B. The theoretical curve was not clearly documented and consequently the plot shows what was available in the literature cited. The data taken between A and B do not fall along a curve consistent with the data at B and C. More data points are needed to fully substantiate the data trend. From this plot, it is concluded that A is in the pre-asymptotic region, whereas B and C are in the self-preservation or asymptotic region of wake development. The velocity profiles at B and C are expected to exhibit similarity, and thus form a baseline case to which velocity profiles of modified flat plates may be compared.

The Wall Effect

The velocity profiles in Figures 11 and 12 show graphically a flow non-uniformity. On the secondary flow side, the velocity increases rather than holding a constant value, for data points near the wall. A similar phenomenon occurs on the high speed side, but to a much lesser degree. Visualization of the flow in this region was conducted with a tuft of string secured to one end of a hand-held rod, and by blowing smoke through the static pressure port on the low-speed wall centerline near A (see Figure 5). Both methods gave no evidence of a recirculation region near the wall. The flow proceeds downstream from the flat plate without separation at the wall. An explanation for the increase in velocity is that the elliptical-wall convergent section, which ends 3/8 in upstream of the plate trailing edge, accelerates the flow near its walls faster than the flow in the passage center, which passes through with less curveature. In the lateral traverses, this effect is not present, since the side walls of the elliptical section do not converge. With a longer elliptical section more gradual channel convergence would occur. Thi. wall effect might be less severe and more uniform flow might be achieved.

The data of non-equal velocities, U less than one, were plotted in Figure 15 with the two-dimensional theoretical similarity curve referenced in Abramovich (Ref 1:28,29). The data at the outside of the wake again suffers from the wall effect. The overall matching in the wake is considered good for all values of velocity ratio. Using the data from the flat plate as a baseline, the data of the modified plate will now be addressed.

The Slotted Plate

The modification to the flat plate trailing edge was the slotted plate as shown in Figure 16. The concept of slotting the trailing edge was chosen as a result of work done by Dr. Arthur J. Wennerstrom. Five slots, each eight millimeters wide, were cut into the flat plate as shown. The simple slotted trailing edge offered the potential of mixing enhancement without the penalty of increasing form drag. Figures 17 through 22 show plots of turbulence parameter and velocity profiles for the slotted plate at A, B, and C, and for the three velocity ratios. Figures 23 and 24 show velocity similarity profiles for the slotted plate for the three velocity ratios.

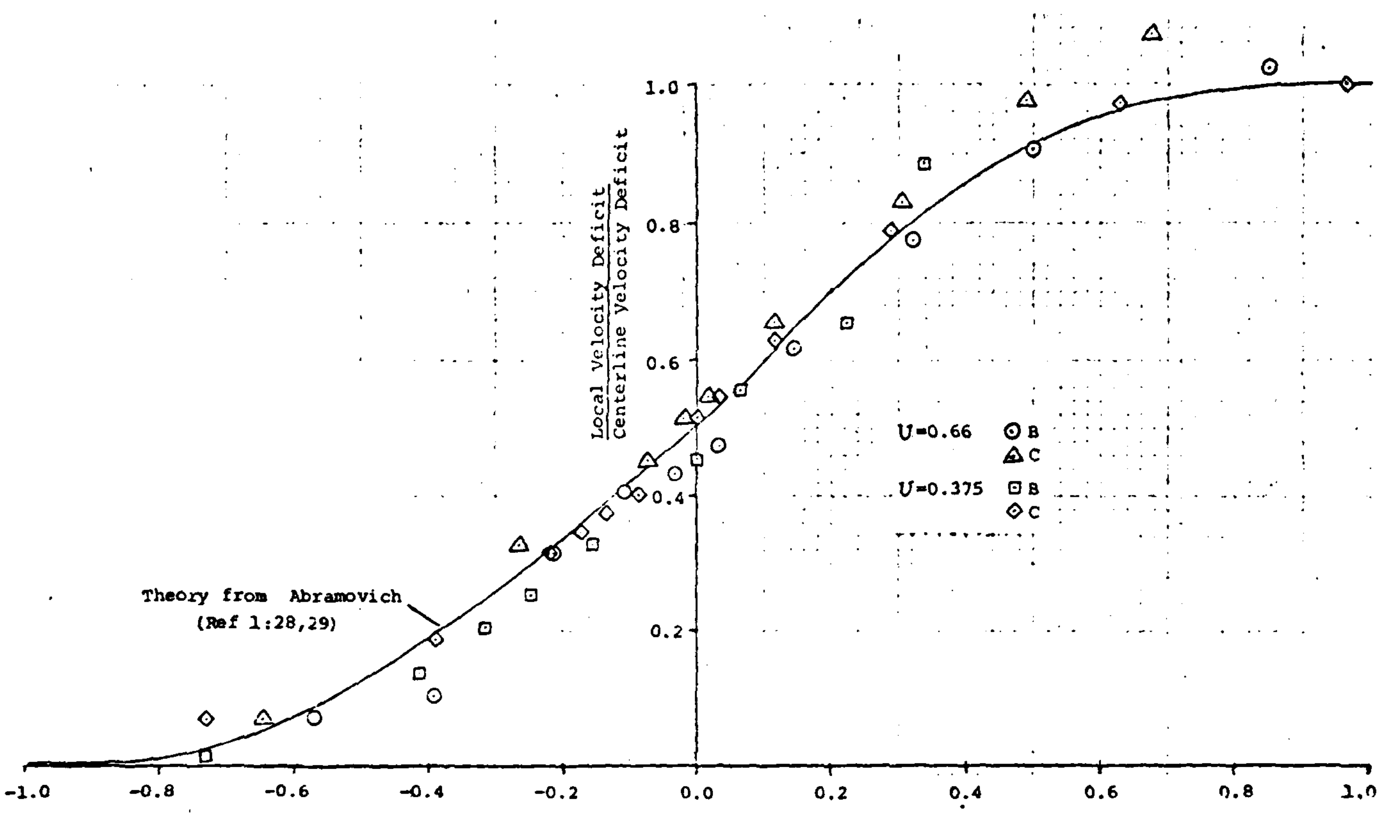


Fig. 15 Flat Plate Similarity Plot, U = 0.375 and 0.66

Plate thickness = 0.05 in

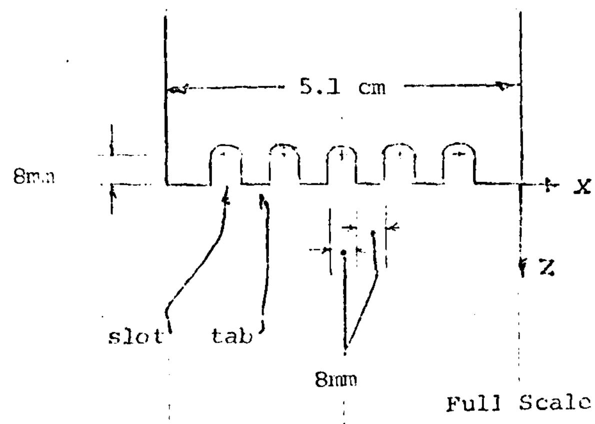


Fig. 16 Slotted Flat Plate

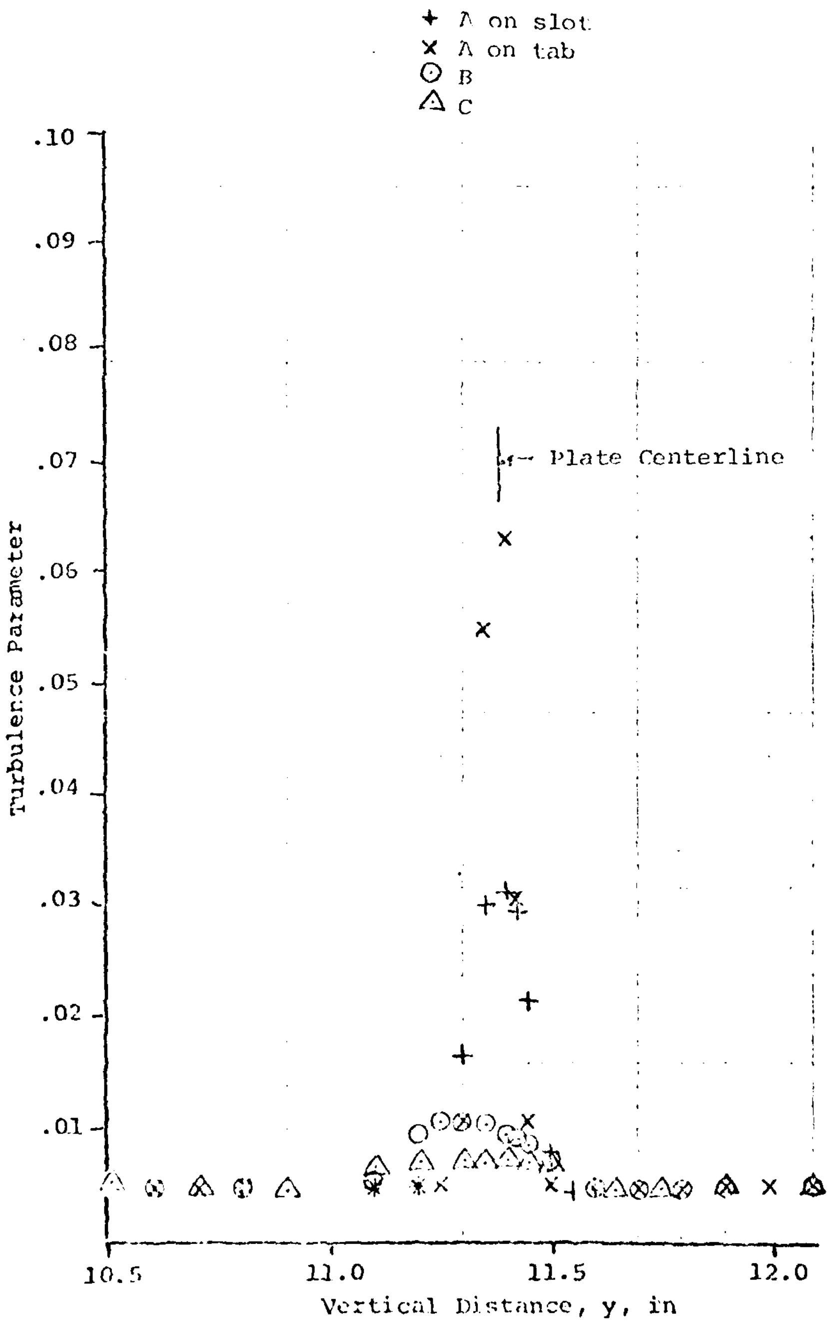


Fig. 17 Slotted Plate Turbulence Parameter, U=1.0

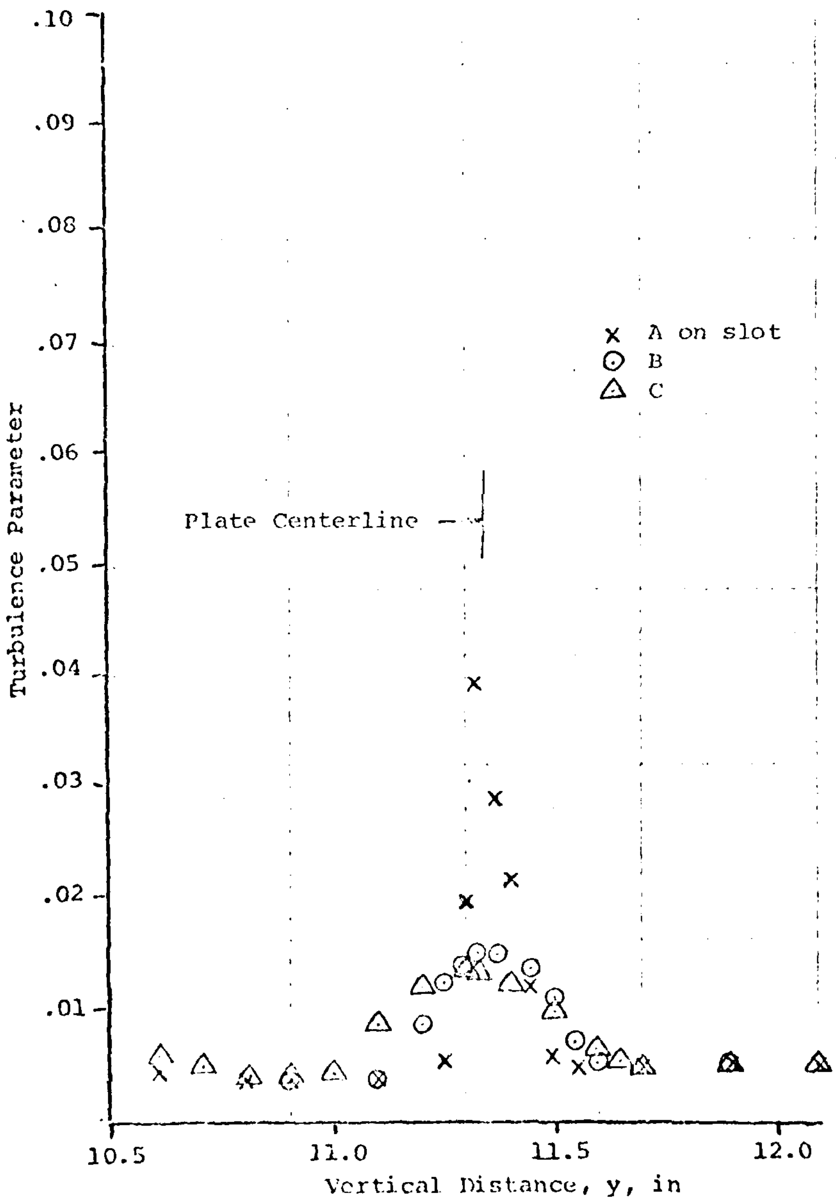


Fig. 18 Slotted Plate Turbulence Parameter, U=0.66

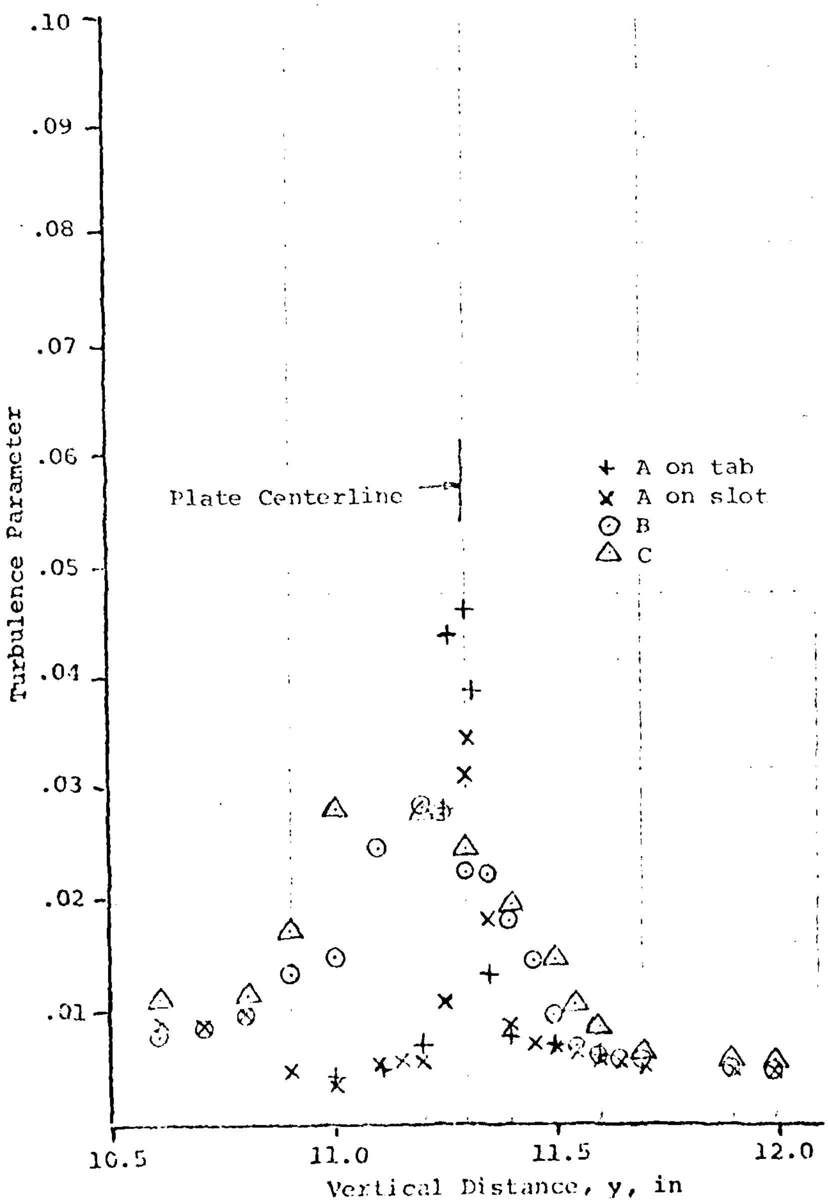


Fig. 10 Slotted Plate Turbulence Parameter, U=0.40

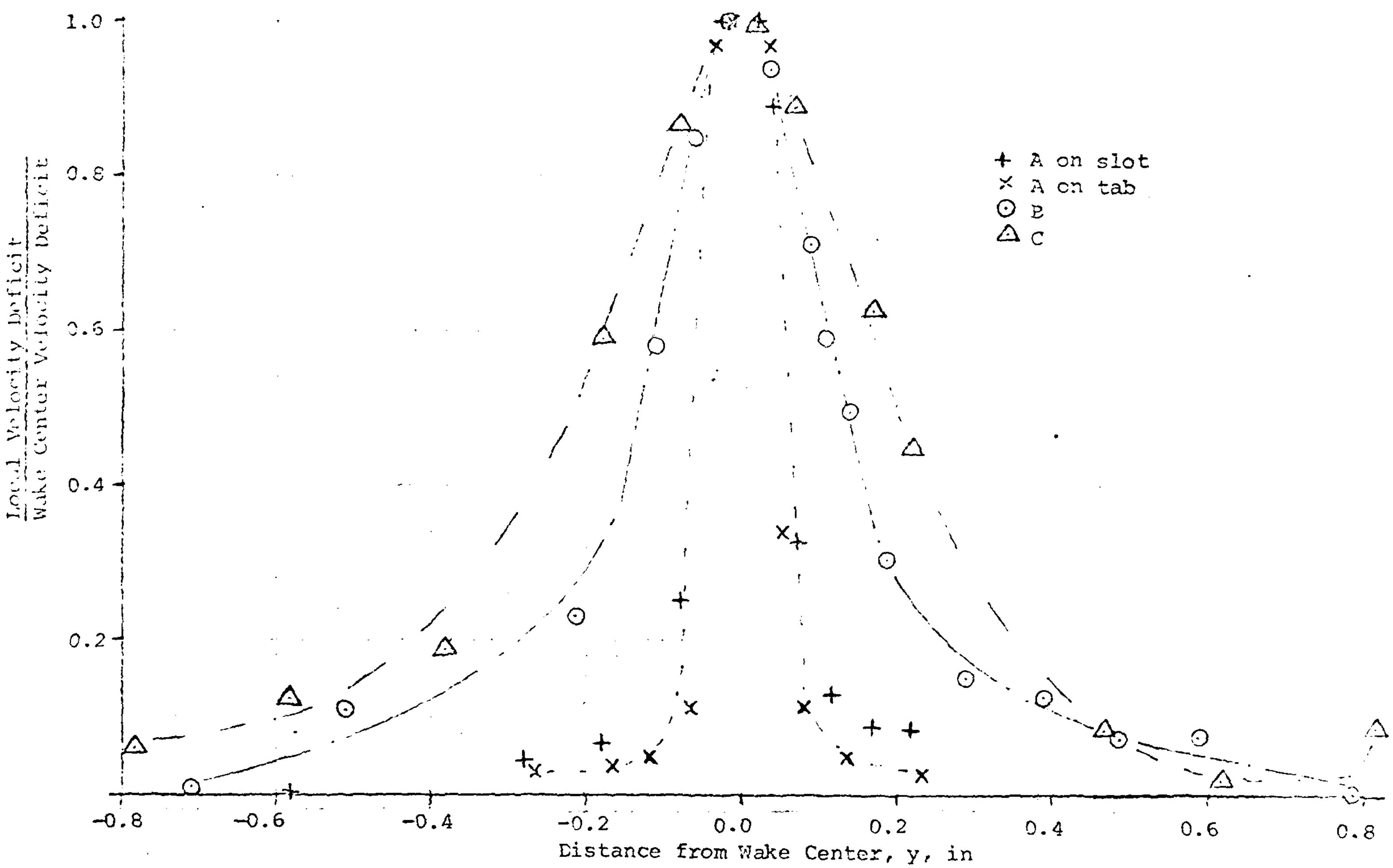


Fig. 20 Slotted Plate Velocity Deficit, U=1.0

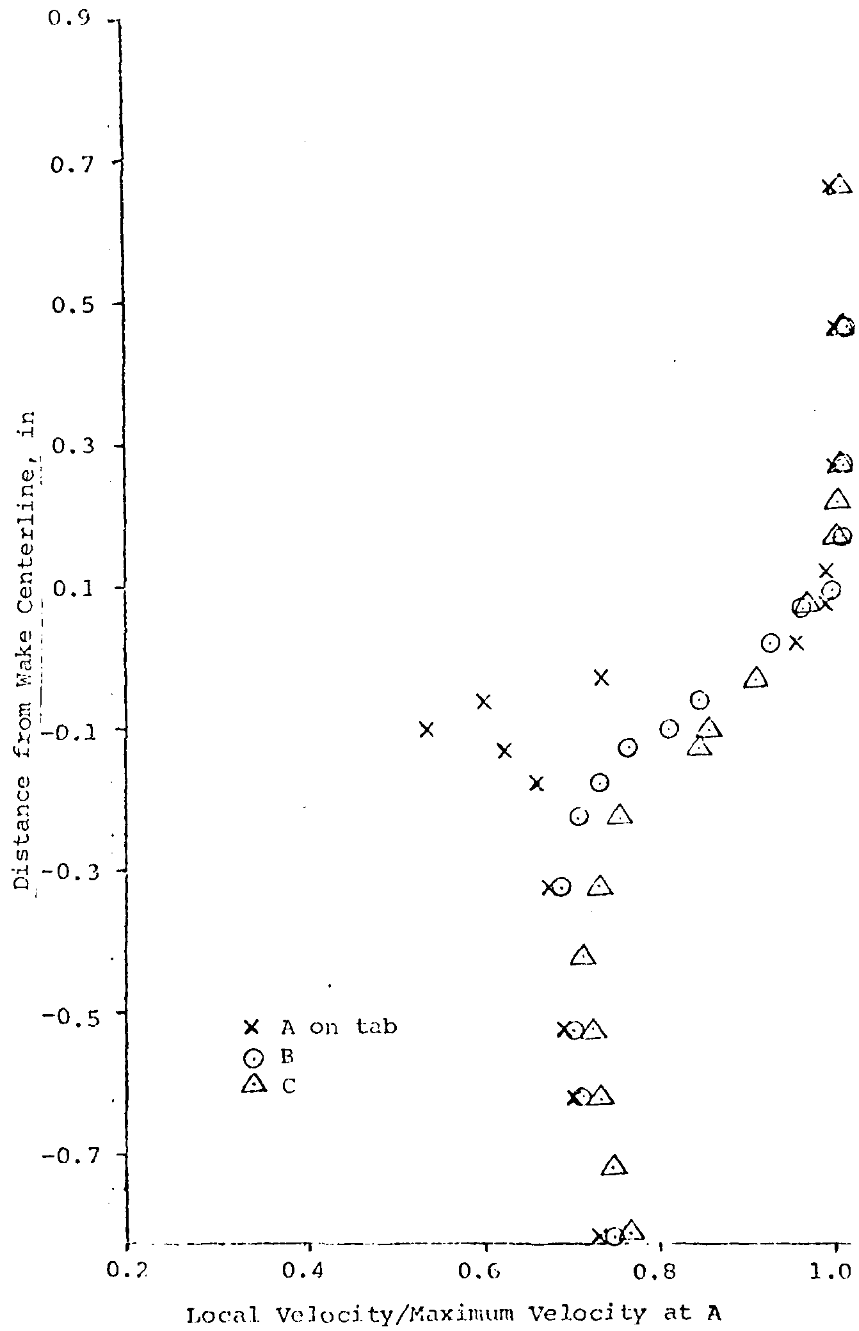


Fig. 21 Slotted Plate Velocity Profiles, U=0.66

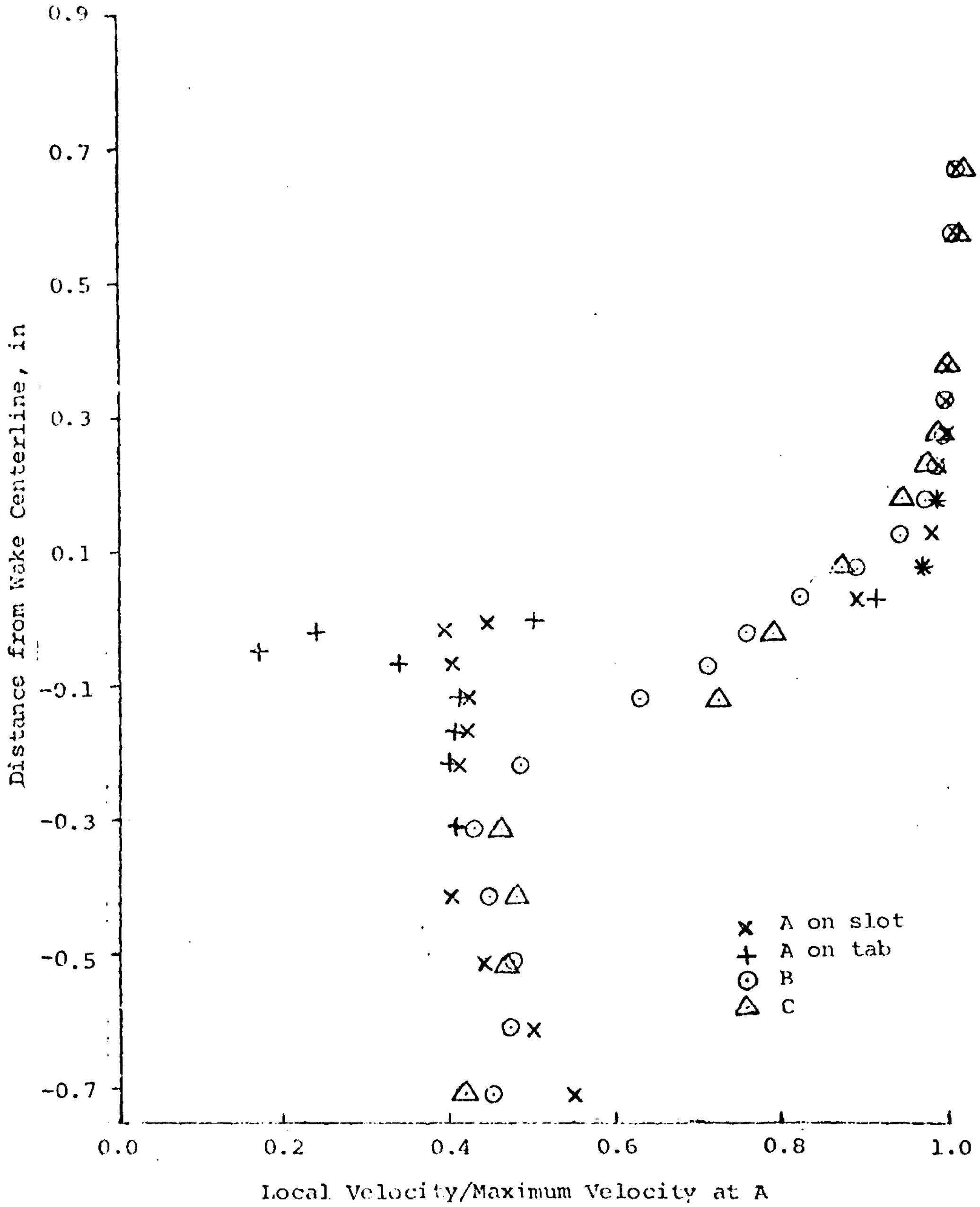


Fig. 22 Slotted Plate Velocity Profiles, $\mathcal{V}$=0.40

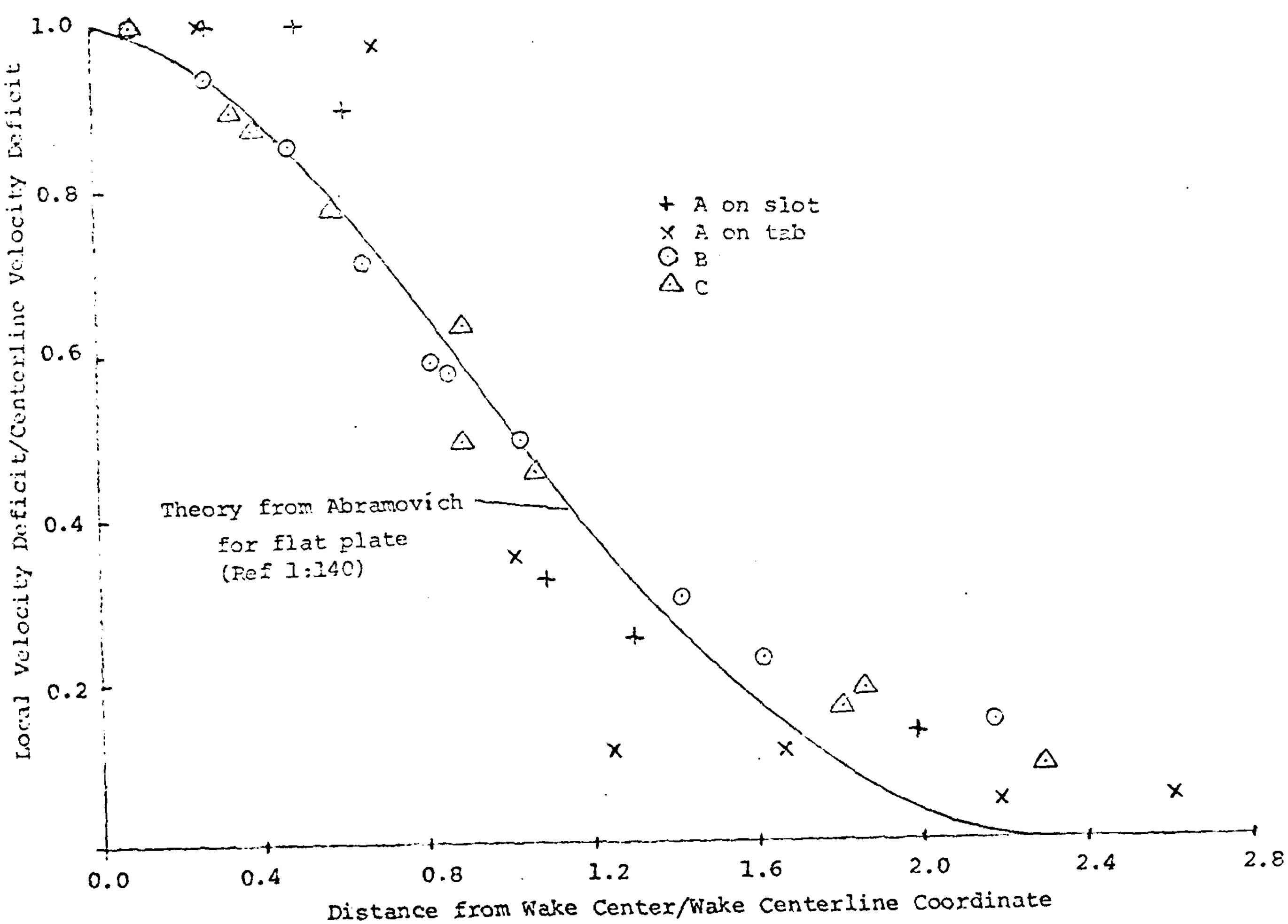


Fig. 23 Slotted Plate Similarity Plot, U =1.0

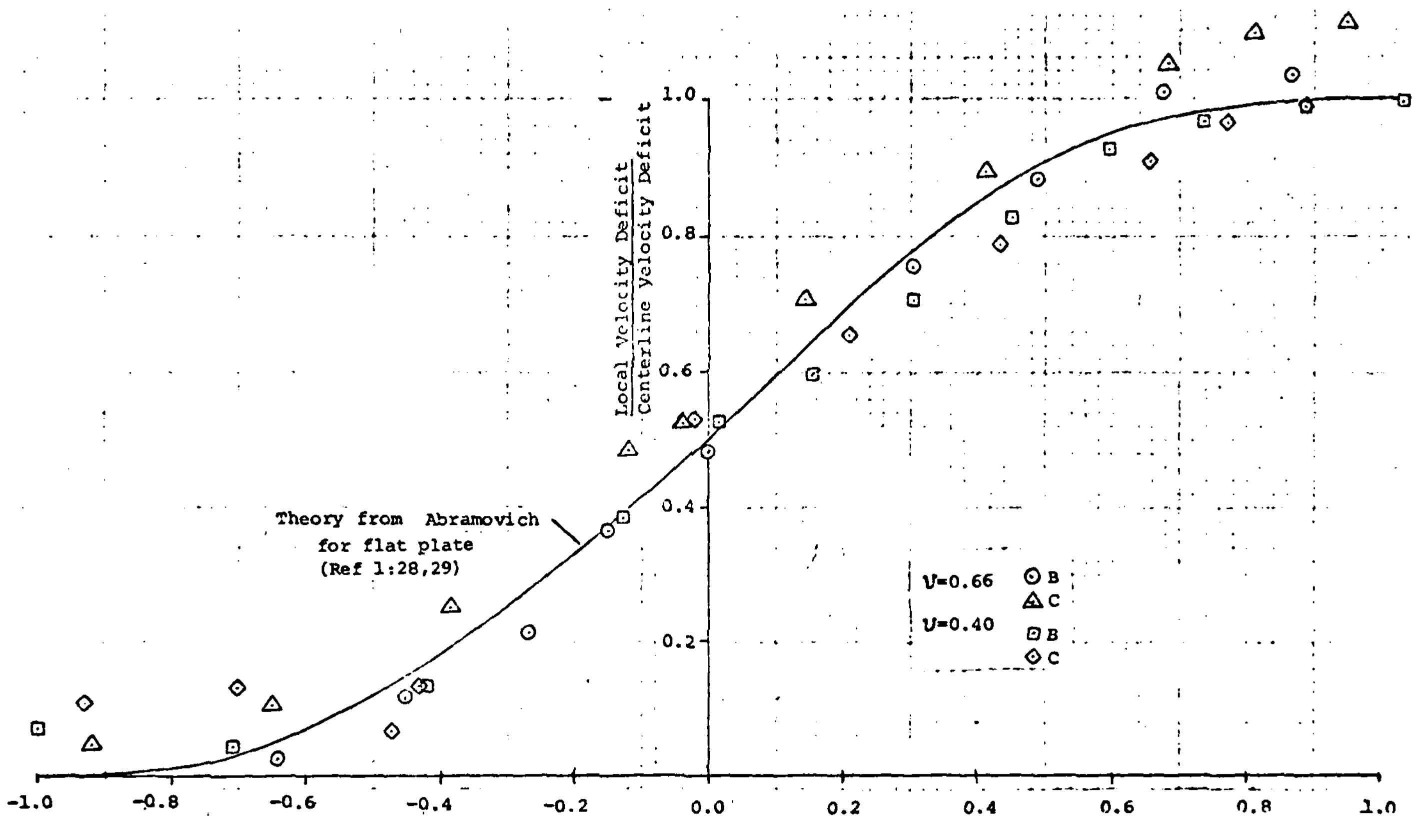


Fig. 24 Slotted Plate Similarity Plot, U=0.40 and 0.66

To gain insight into the effects of the slots on the downstream mixing region, data were taken at U = 1.0 and 0.40 at A, both on the centerlines of the middle slot and an adjacent tab. In general, measurements taken on the tab centerline show lower velocity (Figure 22) and a higher level of turbulence parameter (Figures 17 and 19). The z/D for the tab centerline data at A is 3.0. If the z distance for the probe location behind the slot is measured from the upstream extremity of the slot, the z/D is 6.937. The wake behind the slot is still in the pre-asymptotic region as evidenced by the bad agreement of the data at A with the similarity profile in Figure 23.

The similarity plot of the slotted plate data (Figure 23) shows that at U = 1.0 the data at B and C match the curve with slightly more scatter than the corresponding data for the flat plate. In Figure 24, for U = 0.66 and 0.40, the data at B and C exhibit similarity but with more scatter than the flat plate between abscissae of 0.2 and 0.7. Here the data do not show as much curveature as the theory. This indicates a departure from the two-dimensional flat plate wake similarity which occurs in the high velocity side of the wake.

Comparison of the Slotted and Flat Plate Wakes

From the turbulence parameter plots, the maximum turbulence parameter for each profile was recorded in Table 2. The maximum turbulence data shows that for both plates turbulence parameter decreases with downstream distance, and decays more slowly in the asymptotic region. Maximum turbulence

Table 2

FLAT PLATE U = 1.0	WAKE WIDTH (Velocity Profiles)	MAXIMUM (Turbulence Parameter)	WAKE WIDTH (Turbulence Plots)
A	0.350	0.0652	0.380
B	0.570	0.0173	0.650
C	0.815	0.0120	0.800
DELTA	0.465		0.420
U = 0.66			
A	0.170	0.088	0.300
B	0.280	0.018	0.630
C	0.510	0.015	0.650
DELTA	0.340		0.350
U = 0.375			
A	0.100	0.045	0.300
B	0.315	0.034	0.890
C	0.590	0.031	1.140
DELTA	0.490		0.840
SLOTTED PLATE U = 1.0			
A (on tab)	0.145	0.064	0.300
B	0.560	0.011	0.450
C	0.840	0.007	0.600
DELTA	0.695		0.300
U = 0.66			
A	0.225	0.039	0.370
B	0.265	0.015	0.500
C	0.375	0.013	0.550
DELTA	0.150		0.180
U = 0.40			
A (on tab)	0.245	0.035	0.400
B	0.345	0.029	0.900
C	0.440	0.280	1.130
DELTA	0.195		0.730

NOTE: DELTA is final minus initial wake width.

parameter at a given location in the asymptotic region increases with reduction of the velocity ratio, U. At similar U, the maximum turbulence parameters for the flat plate wakes exceeds those for the slotted plate. This suggests that the flat plate wakes are more turbulent than the slotted plate wakes, and that the turbulence increases with a greater difference in the velocities of the two parallel streams.

Wake width was a major parameter used to compare the mixing regions of the two plates tested. Wake width was measured in two ways. From the turbulence parameter plots the width of the wake was measured as the distance between freestream turbulence levels across the wake. From the velocity profiles, widths of the wakes were measured, taking the boundary of the wake to be the point where the velocity was 0.9 of the freestream velocity on the same side of the wake. The wake growth rate from A to C, called DELTA, is also given. These measurements are presented in Table 2.

For both plates, the wake width increases non-linearly with downstream distance. Theory indicates that the growth of the wake depends on the square root of the downstream distance for a two-dimensional plane wake (Ref 13:734). The width of each velocity profile is influenced by U. At B and C, in Table 2, width is largest when U = 1.0, drops when at U = 0.66, and widens slightly when the velocity difference is greatest.

The wakes measured from the velocity profiles give no conclusive evidence as to which plate generally has the wider wake. For the wake measurements on the slotted plate at A, data taken from the trailing edge of the tab was used since it was at the same z/D as the trailing edge of the flat plate. At A, only when U is not unity, the slotted plate wake is larger. At B, wakes are equal when U = 1.0, larger for the flat plate when U = 0.66, and then larger for the slotted plate when U is 0.40. At C similar ambiguity exists: When U = 1.0, the slotted plate wake is larger; then when U is less than 1.0, the flat plate wake is larger than the slotted plate wake.

Definite trends are seen from the wake widths measured from the turbulence parameter profiles: The wakes at B and C show significant increases in size when the velocity ratio is lowered from U = 0.66. For the flat plate, as the U is lowered, wake width changes slightly at A. At B and C, wakes decrease in width from U = 1.0 to 0.66, but increase by half from U = 0.66 yo 0.375. The slotted plate wake width at A increases slightly with decreasing U, whereas at B and C, little change is seen from U = 1.0 to 0.66. From U = 0.66 to 0.40 the wakes at B and C nearly double.

The widths measured from the turbulence parameter profiles, compared at similar U, show agreement with the results from the velocity profiles only for the cases of U = 0.66 at B and C, where the flat plate wake consistently exceeds the slotted plate wake.

The overall slope of the wake, that is the change in width divided by the change in downstream distance, was assumed to indicate the degree of mixing. The twelve DELTA values in Table 2 represent the final minus initial wake widths. The DELTA was not divided by downstream distance since the distance from A to C was constant for all cases. In all but one of the twelve calculations, the flat plate wake is seen to have a larger slope than the slotted plate wake, and hence grows at a faster rate. This supports the conclusion that the slotted plate is not as good a mixer as the flat plate, as tested here.

An optimum U for mixing was not found. The wake growth rate for both plates shows a minimum when U = 0.66, and then doubles when the secondary stream velocity is reduced to about forty percent of the primary stream velocity. If a velocity ratio for maximum wake growth exists for either plate, it must be less than U = 0.66 unless other devices to enhance mixing are employed.

The validities of the methods used to measure wake characteristics will now be discussed. The wake widths derived from the turbulence parameter plots are based on readings of RMS hot film output. These readings were easily obtained, since the readings on the RMS meter had little fluctuation in general. As previously discussed, the freestream turbulence parameter is analogous to turbulence intensity, and so the widths measured from the turbulence parameter plots should be a dependable result. The wake widths based on the velocity plots are judged to be less accurate. They are based solely on the readings of the mean hot film output voltage. Accurate average values of the mean voltage was difficult to obtain due to the fluctuations in the output. Since the widths based on the velocity profiles show no definite trends when the two plate wakes are compared, the turbulence parameter widths are considered as being more accurate. Wake growth rate can be taken to represent the transverse fluctuating component of velocity in the wake, and hence the rate of growth of the wake represents the mixing (Ref 1:11). In Table 2, the DELTA values indicate this wake growth rate. The DELTA values of the velocity profiles agree with those of the turbulence parameter profiles. Both suggest that the flat plate wake has the more rapid growth rate. Thus, the wake growth rate based on the velocity profiles is considered to be a more accurate representation than the wake widths based on the velocity profiles.

Error Analysis

In general, the data shows consistency. The velocity and turbulence parameter points fall along curves with regularity and little scatter. The day-to-day repeatability of the data was confirmed on several occasions. Also, certain data points were successfully repeated during the same test run.

Error in hot film measurements arise from many factors, including dust accumulated on the sensor from the flow, and changes in ambient temperatures. Tests were all run between 74 and 81 F. Ambient conditions were fairly stable during the test period, but not all dust was removed from the flow. To account for these sources of error the probes were re-calibrated four times during the research. The maximum shift in the calibration curves (Figures A-1 and A-2) shows an error of less than three percent. This error is taken as representative of the error in the data, due to the electronics and hot film variations.

Cebeci and Smith report typical turbulence levels encountered in wind tunnels (Ref 7:13). Turbulence intensity of 0.2 to 0.4 percent corresponds to flow in a good tunnel without screens, and 1.0 percent to flow in a poor wind tunnel. Typical freestream intensity in this apparatus is 2.2 percent, and uniform.

It should be noted that since the single element hot film probe was not rotated in the flow, the voltage fluctuation measured represented only two of the three orthogonal velocity fluctuation components present in the flow. These were fluctuating components in planes perpendicular to the wire. The third component was not accounted for in the calculation of turbulence intensity, and so the calculated turbulence intensity of 2.2% is lower than the real value.

Due to the length of the probe support and the turbulent wake, the probe vibrated at approximately 1/8 in amplitude. Probe vibration gives the hot wire an oscillating component of velocity of its own in relation to the flow; and thus introduces a source of error to the data. When the vibration was held to a minimum no noticeable change was detected in the instrument readings. Probe vibration is not considered to be a significant source of error.

V. CONCLUSIONS AND RECOMMENDATIONS

From the results of this study the following conclusions are drawn:

1. The turbulence behind the flat plate is greater than that behind the slotted plate. Moreover, the flat plate wake grows at a faster rate than the slotted plate wake. The flat plate wake mixes the two streams of air better than the slotted plate wake.

2. No velocity ratio of the two streams was found to maximize the mixing for either plate. From turbulence parameter profiles, the increase of wake width with downstream distance was found to double for both plates, from the case of equal velocity in both streams to the case of the slower stream reduced to about forty percent of the faster stream. If an optimum velocity ratio for mixing exists, it is less than 66 percent. The maximum level of turbulence parameters, hence turbulence intensity, was found to increase in proportion to the difference in the velocities of the two streams.

3. The facility is determined to be of acceptable quality for the qualitative study of the mixing region of two parallel air streams as seen from the flat plate data. It provides turbulence intensity of 2.2%, which is uniform in tl sideways direction. Flow in the plane of wake growth, or vertical direction exhibits accelerated flow near the upper and lower passage walls. This is a constant effect in the

apparatus, and so influences only the flow near the walls of each test independent of the configuration tested.

4. Of the methods used to characterize the mixing regions of each plate the turbulence parameter plots were considered to be most accurate. Wake growth rates based on the velocity profiles agreed with the wake growth rates based on the turbulence parameter profiles. Widths of the wakes based on the velocity profiles did not give conclusive results.

Recommendations

1. The freestream velocity profiles in the test section are uniform in the sideways, but not the vertical direction. This effect, which occurs in the plane of wake growth, is most noticeable with decreasing velocity and is believed to be caused by the elliptically curved convergent section. An ellipse of longer major axis would decrease this wall effect. For the purpose of comparing wake sizes, this wall effect is believed to be a constant tunnel effect and not dependent on the modification being tested.

2. Use of a thinner plate would decrease the thickness of the wake and thus restrict its propagation into the wall effect region. The effect of variation of slot geometry on the mixing process could then be studied.

3. Optical systems such as Schlieren, could be used to visualize the wake and wall boundary layers in the apparatus as constructed. By installing a suitable gas injection device between the plate leading edge and the last

screen, helium could be used to seed one stream to enhance the quality of the image.

4. Investigation of the size of the turbulent eddies in both cases is warranted. Larger eddies would indicate better mixing. A hot wire anemometer or laser velocimeter could be automated with a data analysis system to enhance the research effort.

5. It should be noted that the hot film length was the same order of magnitude as the slot width dimension. More dependable data could be attained near the slots by using a smaller probe.

6. Certainly other trailing edge modifications are imaginable. If the plate is partially severed by a series of longitudinal cuts, and the resulting tabs are bent alternately up and down, with vertical walls joining the adjacent sides of each tab, a modification is formed which should angle the flow up and down. Opposing sets of vortices should be created in the shear layers of adjacent streams, which would enhance mixing. Slots cut into these tabs would constitute another modification.

7. The freestream turbulence of these tests was low in comparison to that in actual engineering problems. With the application of cloths to change the velocity ratio, the freestream turbulence of the slower stream was also changed. A logical extension to this study would be to study the effect of freestream turbulence intensity on the growth of the wakes.

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APPENDIX

Hot film calibration was conducted with a single-element hot film probe mounted in the core flow of a metering orifice jet. Procedures for calibrating the electronics are described in the Thermo-Systems manual (Ref 11:1-1+). The probe and accompanying electronics were exactly as set up for the experiments. Facility air was piped through a metering unit to a stilling chamber with a flow screen upstream of the metering orifice. One side of a 100 inch manometer was connected to the stilling chamber and the other side was open to the ambient pressure.

With the hot film electronics turned on and warmed up, the air was allowed to flow out of the orifice at a set pressure differential. Several pressures were used to obtain a voltage versus velocity calibration curve over the range of data expected.

Velocity was calculated in feet per second from:

$$U = \sqrt{2 g_c R T \left(\frac{\gamma}{\gamma - 1}\right) \left[1 - \left(\frac{P_{amb}}{P_T}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where: g_c = 32.174 lbm-ft/lbf-sec^2

R = 53.35 lbf-ft/lbm-R, gas constant for air

T = F + 460, ambient temperature, deg Rankine

γ = 1.4, ratio of specific heats for air

P_{amb} = Hg x 13.6, barometric pressure converted to in of water

P_T = total pressure of the chamber, in water.

Figure A-1 shows calibration curves for sensor L266, and Figure A-2 shows sensor K478 calibration data. The deviation of the calibration curves from week to week was less than 3 percent.

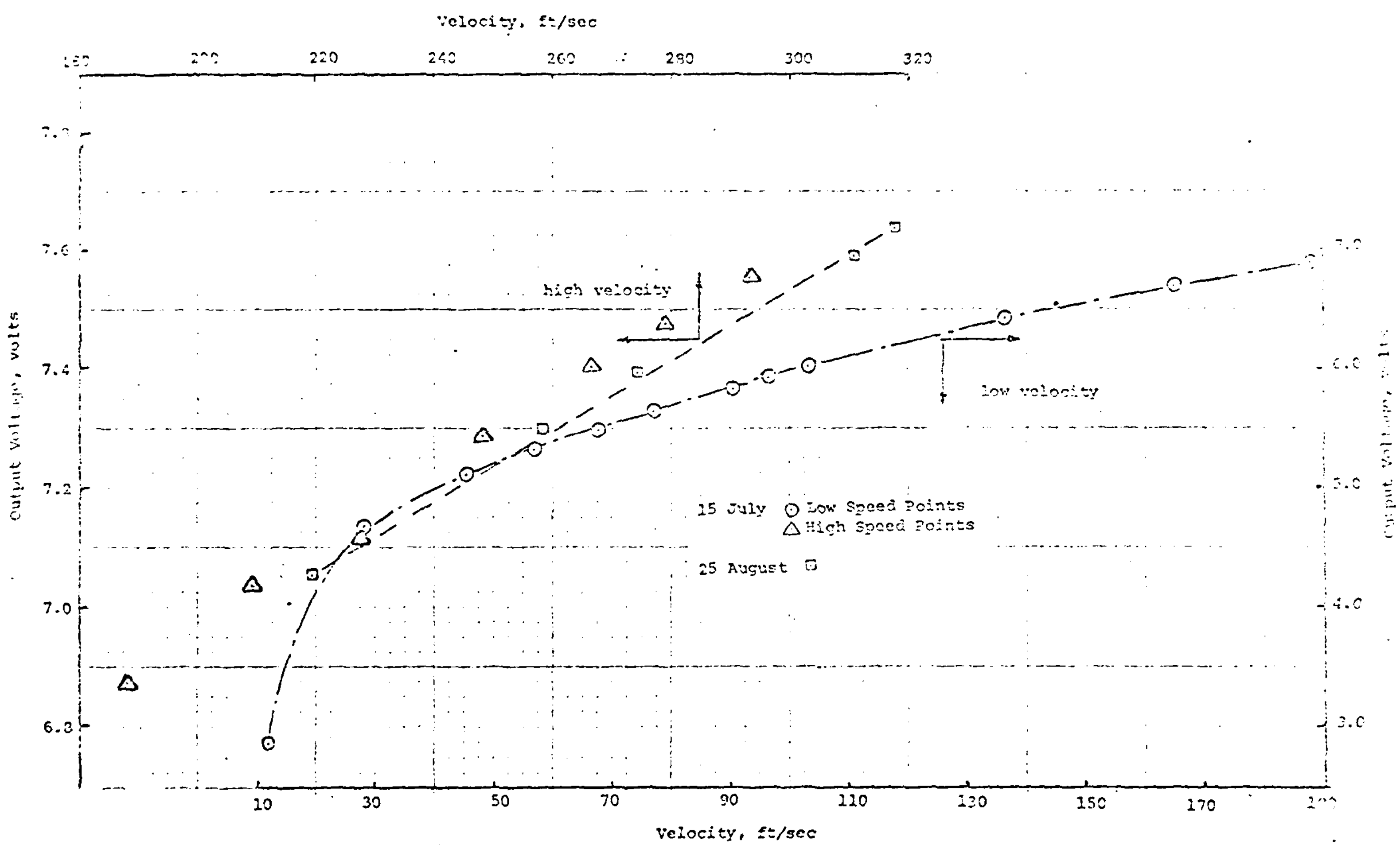

Fig. A-1 Sensor L266 Calibration

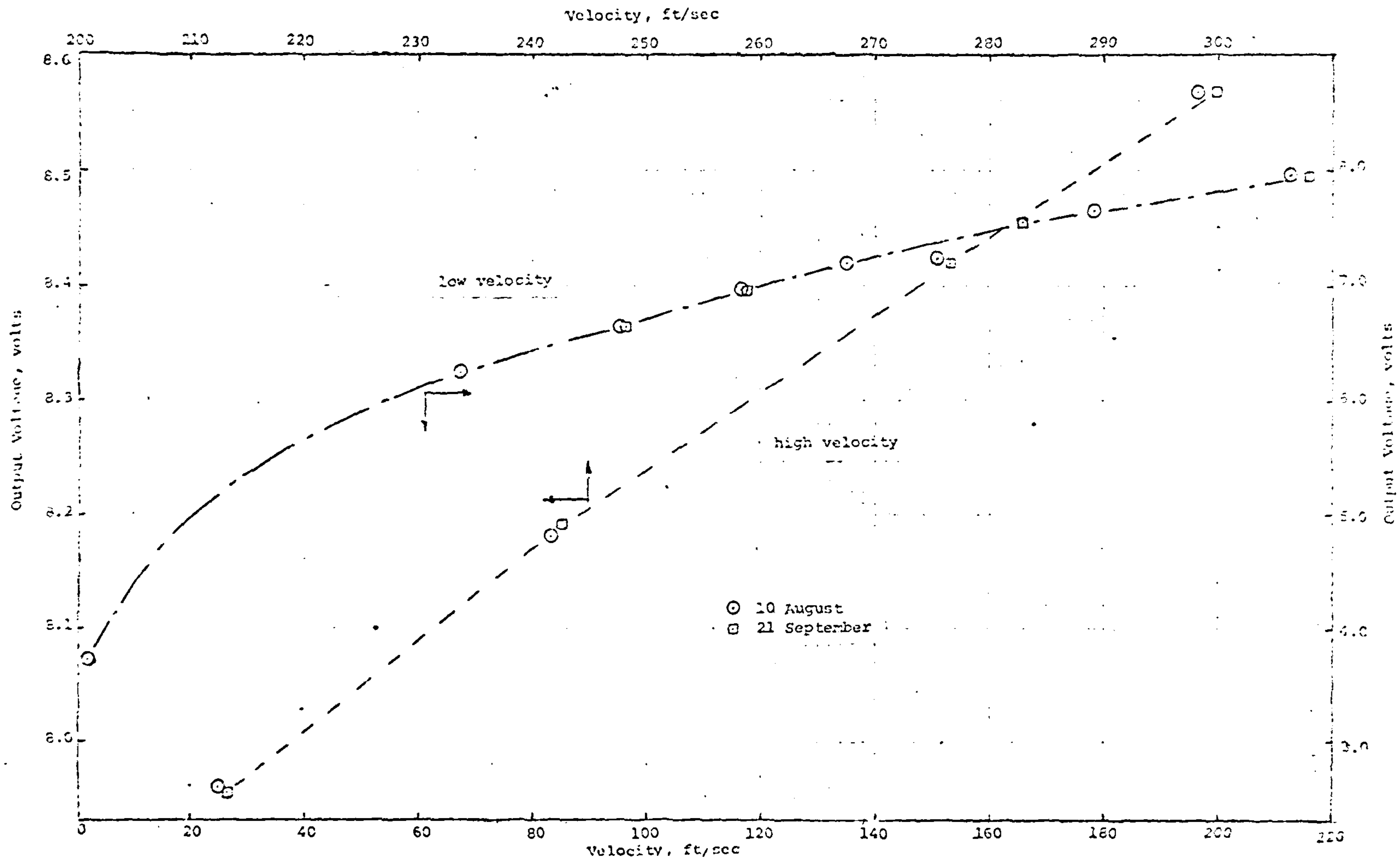

Fig. A-2 Sensor K478 Calibration

VITA

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The objective of this thesis is to study ways to enhance the mixing of two parallel streams of air by modifying the trailing edge of a separating wall. An apparatus was designed which achieved two-dimensional, good quality flow near the center of the test section passage, with freestream turbulence intensity of 2.2 percent. Measurements of the wake were made varying the velocity of one stream down to 37.5 percent of the other stream velocity, both in and upstream of the asymptotic region of the wake. A single element hot wire was used to measure velocity and RMS readings. The flat plate trailing edge was then (contd)

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slotted with five, eight millimeter slots and re-tested. The higher turbulence and wider wake of the flat plate indicate that the slotted plate wake does not achieve as good mixing as the flat plate wake. No velocity ratio of the two streams was found to maximize the wake growth for either configuration. Wake growth doubled when the slower velocity was 0.40 of the faster velocity.