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The effects of grid-generated, free-stream turbulence up to levels of 7.5% were investigated in a low speed water channel. The distribution of turbulent Prandtl number in the flat-wall region was found to be the same in water as in air, contrary to expectations based on the literature.

The effect of Prandtl number on wall trace visualizations of heat transfer was investigated with a liquid crystal surface in a water tunnel. Heat transfer images were dominated by events within the sublayer, while fluid mechanics visualizations show effects from far out in the boundary layer.

A series of experiments were done in a high turbulence air tunnel (16%, uniform across the tunnel) to investigate whether or not an abrupt change in flow passage size, with no flow acceleration, would affect heat transfer. A membrane was placed at 1/3 and 1/6 of the passage height in a heat transfer tunnel, reducing the largest possible normal scale of the turbulence by that same ratio. There was no significant change in the distribution of heat transfer on the surface under the membrane.

A second investigation involved wake-like turbulence interacting with turbulent boundary layers. A wind tunnel experiment is described where spatially-inhomogeneous turbulence, in the absence of mean-velocity variations, is generated by a graded grid which produces intensity levels of 10% at its top and hardly any at its bottom, the part close to a flat wall. Turbulence from the grid diffuses down the intensity gradient and spreads into a turbulent boundary layer on the flat wall.

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THE EFFECTS OF FREE STREAM TURBULENCE AND SURFACE CURVATURE ON BOUNDARY LAYER FLOW AND HEAT TRANSFER

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March 5, 1992

ABSTRACT

Two investigations are reported: an experimental study of several aspects of the fluid dynamics and heat transfer of low Reynolds number turbulent boundary layers on flat and curved (concave) walls, and a study of the effects of wake-like turbulence interacting with a turbulent boundary layer.

In the first investigation, the effects of grid-generated, free-stream turbulence up to levels of 7.5% were investigated in a low speed water channel where the Prandtl number is high relative to gas (air) flows. Heat transfer was augmented both by curvature effects and free-stream turbulence and cannot be predicted simply by a Prandtl number corrector applied to air data. The distribution of turbulent Prandtl number in the flat-wall region was found to be the same in water as in air, contrary to expectations based on the literature. Following on from this experimental work, a direct numerical simulation study has been initiated in order to improve our understanding of ultra-high free-stream turbulence heat transfer

The effect of Prandtl number on wall trace visualizations of fluid mechanics and heat transfer was investigated with a brief series of tests involving a liquid crystal surface in a water tunnel. The preliminary conclusion is that the heat transfer images seem to be dominated by events within the sublayer, while fluid mechanics visualizations show effects from far out in the boundary layer. The difference is attributed to the effects of Prandtl number.

A series of experiments were done in a high free-stream turbulence air tunnel (16% turbulence uniformly across the tunnel at entrance) to investigate whether or not an abrupt change in flow passage size alone, with no flow acceleration, would affect heat transfer. An abrupt change in passage size is one feature of the situation in the first stage nozzle ring of a gas turbine, when flow from the combustion chambers first enters the small passages between the vanes. The reduction in passage height was accomplished by inserting a thin membrane into the tunnel above the heat transfer surface, after the free-stream flow field was well developed. The membrane was placed at 1/3 and 1/6 of the passage height in a heat transfer tunnel, reducing the effective tunnel height and thus also the largest possible normal scale of the turbulence by that same ratio. There was no abrupt change in the heat transfer downstream of the leading edge of the membrane and no significant change in the distribution of heat transfer on the surface under the membrane. This is contrary to expectations based on current turbulence models. It appears that the effects of scale are not yet well enough understood and that "separate effects" studies such as these may be a fruitful way to investigate the issue.

The second area of investigation involved wake-like turbulence interacting with turbulent boundary layers. A wind tunnel experiment is described in which spatially-inhomogeneous turbulence, in the absence of mean-velocity variations, is generated by a graded grid which produces intensity levels of 10 per cent at its top and hardly any at its bottom, the part close to a flat wall. Turbulence from the grid diffuses down the intensity gradient and spreads into a turbulent boundary layer on the flat wall.

1. INTRODUCTION

Curved surfaces exposed to high heat loads occur in many power systems of interest to the Air Force and are frequently the most vulnerable components of a system: i.e., nozzles in rockets and ramjets, blast tubes, blades and vanes in gas turbines, and internal flow passages. There is ample evidence that convective heat transfer to a curved surface is significantly different (by as much as ± 20 to ± 40 percent) than on a flat surface and that these effects are controlled by the fluid mechanic behavior. Similar and even larger effects are observed when heated surfaces are exposed to flow streams with moderate to high levels of free-stream turbulence. In practice, the turbulence has a number of sources including upstream blade wakes and combustion chambers. The discrepancies between measured and predicted surface heat transfer rates are well beyond the margin of safe design, and one concludes that the current state of the art does not permit sufficiently accurate prediction of these effects. The fluid mechanic mechanisms responsible for heat-transfer augmentation under high turbulence flows have been postulated, but firm experimental evidence is only now being developed to investigate these hypotheses.

The main goals of the present program are (i) to identify and quantify the mechanisms responsible for the increased heat transfer for modest to high levels of free stream turbulence over boundary layers on flat and concave curved surfaces, and (ii) to begin to investigate how these mechanisms may be incorporated into turbulence models for predictive purposes.

Three experimental facilities were used in the work described here: a water tunnel with flat and concavely curved test surfaces (with and without turbulence generating grids), a high turbulence air tunnel using a simulated gas turbine combustor turbulence generator (16% free-stream turbulence uniformly across the channel at entrance), and a 30x30 inch, general purpose wind tunnel.

In the water facility, a turbulent boundary layer over a flat surface which leads into a concave region has been subjected to grid-generated free-stream turbulence at levels of 5 to 7%. Both the heat transfer and the fluid mechanics resulting from this situation have been measured in detail. In the high turbulence tunnel, the effects of turbulence scale on heat transfer have been investigated by dividing an established turbulent flow into two paths, one of small height, and observing the effect of the change in passage height on heat transfer and turbulence characteristics. In the 30x30 wind tunnel, a flat wall, turbulent boundary layer is being perturbed by a spatially-inhomogeneous free-stream turbulence field intended to simulate the effect of upstream blade-wake turbulence. The approach has been to conduct experiments which allow visualization of the flow structure, measurement of the mean and turbulent motions in the structure, and simultaneous measurement of heat transfer rates.

In all of these studies, the end objective is to develop or refine predictive models to broaden the range of accurate prediction of fluid mechanic and heat transfer behavior.

2. OBJECTIVES

2.1 Studies of free stream turbulence and concave wall curvature in a water channel with heat transfer

2.1.1 Fluid Dynamic Studies (Johnston) had three initial objectives. Objective 4 was added during the last year of the study:

(1) To complete the current study of the turbulent boundary layers on flat surfaces at low and moderate levels of free stream turbulence.

(2) To examine the effects of elevated levels of free-stream turbulence, on the flow as it develops from a flat plate layer to a concave curved layer. In particular, to investigate the interactions that result from the combined effects of elevated free stream turbulence and the concave instability mechanisms known from previous work.

(3) To work closely with the related heat transfer phase to develop new methods of using the present flow measurement techniques for improved diagnostics of the steady and fluctuating flow and thermal properties.

(4) To initiate a direct numerical simulation (DNS) of ultra-high free-stream turbulent heat transfer in order to improve physical understanding of the augmentation processes, and to provide basic data for improved turbulence models.

2.1.2 Heat Transfer Studies (Moffat) has three objectives:

(1) To understand the physical mechanisms by which concave curvature and high free-stream turbulence affect surface heat transfer in terms appropriate for guiding modeling efforts.

(2) To develop the data base and calculation procedures needed for predicting heat transfer in air from data taken in water for high turbulence and curved wall flows.

(3) To improve measurement techniques appropriate for heat transfer studies in complex flow fields.

2.2 Studies of Wake-Like Turbulence Interacting with Turbulent Boundary Layers (Bradshaw)

As demonstrated in work at Imperial College (Baskaran, Abdellatif & Bradshaw 1989 and Baskaran & Bradshaw 1989), the primary effect of blade wakes on a following blade row is to reduce the onset speed when the downstream blades are in the wakes of the upstream blades and to increase the onset speed when they are not (the mass flow rate being constant). Because drag depends, approximately, on the square of onset speed, the final effect is to increase drag. This mechanism would operate even if the wakes were non-turbulent; and the several experiments in the literature, in which effects of blade wakes have been equated to "turbulence" rather than the "ordered unsteadiness" just described, have confused the situation.

Following the Imperial College work, we at Stanford have developed and used a graded turbulence grid, to produce a flow with constant velocity but circumferentially (actually vertically) - varying turbulence intensity. When the flow from the grid passes over a horizontal flat plate representing a downstream blade, the highly-turbulent flow from the top half of the grid diffuses downwards to meet with the plate boundary layer. This represents the effect of the turbulence in a blade wake on a downstream blade, omitting any effect of mean-velocity variations.

Analysis of the final results is still in progress following the departure of the research assistant (and will be carried on by a summer student), but when complete, the data should demonstrate the comparative effects of:

(i) highly-inhomogeneous turbulence from the blade row just upstream
(ii) ordered unsteadiness from the blade row just upstream
(iii) nearly-homogeneous turbulence, with comparatively small spatial variations of mean velocity, as a cumulative effect of all upstream rows.

3. RESEARCH RESULTS

3.1 Studies of free stream turbulence and concave wall curvature in a water channel with heat transfer

3.1.1 Fluid Dynamic Studies (Johnston)

The objectives of this phase of the research were partially met in 1989 through the publication of a major research report, Johnson and Johnston (MD-53, Nov.1989), and several papers. Their results are summarized are:

(i) Decay rates of the grid generated, nearly isotropic free-stream turbulence in the straight sections of the channel were quite normal, but in the curved region of the channel the rate was lower. In our flow it is believed that mean streamline curvature didn't affect dissipation, but a small, residual turbulent shear stress interacts with the mean strain due to curvature to produce added turbulence energy as one follows a curved mean streamline.

(ii) Flow visualization using the hydrogen bubble method in the wall layer regions for cases with free-stream grid generated turbulence of 5.0 to 7.5% were very similar to visualizations with a low turbulence free-stream, both on the flat wall region and in the region of concave curvature. Other evidence, based on detailed measurement of all three velocity fluctuations (u', v', w') well down into the viscous sublayers, suggests that the near wall flow structure is hardly changed for 5.0% turbulence levels, but starts to be affected at 7.5%. Wall layer scaling, below y+ of 50 is universal for all measured variables for 5% turbulence, and starts to show the effect of the free-stream at 7.5%; the most noticeable effect being in the w' (rms) profiles near the wall.

(iii) Mean flow parameters and velocity profiles were obtained for the flat and concave wall regions, with and without grid-generated turbulence. Momentum thickness Reynolds number was 1,400, typically. High turbulence, whether grid produced, or produced naturally in the unstable outer layers of the concave wall flow, gives mean velocity profiles are that are flattened (the "wake" portions of the profiles decreased and even become negative). For the flat wall case, the fractional increase in wall stress. $\Delta c_f/c_{fo}$, follows Castro's low Re version of Hancock and Bradshaw's correlation at low corrected turbulence levels, but $\Delta c_f/c_{fo}$ levels out at about 0.18 for higher levels where extrapolation of Castro's data, gives values as high as 0.25. The combined effects of the added mixing and higher turbulence levels in the unstable concave wall layer also increase wall friction, but the effects are not simply additive. The added shear stress due to concave curvature becomes the dominant effect after a region of growth of the of the large scale eddies that result from the concave instability.

(iv) A new conceptual model of the effects of free-stream turbulence on wall stress and wall heat transfer is proposed. It is based on the observations of this flow study, and the work of others on the related heat transfer problem; in particular, the work reported by Hollingsworth, Kays and Moffat (HMT-41, 1989), and carried out in parallel with this program. The model employs the concepts of active and inactive turbulence (Townsend and Bradshaw) to explain why c_f appears to saturate at a given level while free-stream turbulence increases, but Stanton number, St, continues to increase. The model recognizes the vector nature of the instantaneous wall shear stress, and concludes that St should be proportional to a c_f based on the mean magnitude of the total wall shear stress, not just the mean of its streamwise component. The implications of this model are yet to be investigated in detail.

The DNS work, objective (4), initiated in the final year of the grant is incomplete, but we are close to producing useful and significant results. Having coded the problem for solution on the massively parallel Connection Machine at NASA Ames, the code validation phase of the project is underway. The problem being solved is a decaying free-stream flow over a wall that moves downstream at the free-stream speed. The wall is held at a temperature different from the free-stream fluid in order to directly calculate the instantaneous and mean convective heat transfer rates due to the turbulence Because there is no mean velocity boundary layer, the convective heat transfer is controlled by the free-stream turbulence and its interaction with the wall. This work is being conducted jointly with one of Prof. P. Moin's students who is concentrating on studies of the velocity field. Our work concentrates on the thermal or scalar transport part of the problem. The code is currently being run with grids as large as 512x256x128 points in order to accommodate the highest practically-achievable turbulence Reynolds numbers. Preliminary results show that, with freestream microscale Reynolds numbers near to 100 at the leading edge of the moving wall, the Stanton number is enhanced by up to 40% over the solution obtained for the case where the free-stream turbulence intensity is zero.

3.1.2 Heat Transfer Studies (Moffat)

One objective of this part of the program was to elucidate the physical mechanisms whereby concave curvature caused an increase in heat transfer. This work was done in the water tunnel. Measurements were made of the thermal and hydrodynamic characteristics of the boundary layer at different locations in the curve, including mean profiles, fluctuating profiles, and spectra of both velocity and temperature. These results were reported by Hollingsworth, Kays, and Moffat, 1989, (supported by this AFOSR grant)[1].

The increase in heat transfer associated with concave curvature is confirmed to be the result of increased turbulence activity caused by transitory structures developed in the outer region of the boundary layer. Evidence of these structures can be seen in the outer region spectra, but not in the inner, hence we believe theses structures do not directly impinge on the surface. This supports our previous finding that the transitory roll cells observed in the outer region of the boundary layer do not cause local increases in h , at least in water boundary layers, but simply cause patterns in the wall-layer streaky structure called "splats". These were first reported by Simonich and Moffat[2], from a study also supported by AFOSR, and are now believed to be the wall traces of the shear stress field developed when packets of inflowing fluid are deflected into the x and z directions.

Several important aspects of the temperature distribution in the boundary layer were found to be unaffected by concave curvature. The near-wall mean temperature distribution is the same in the curved region as in the flat region, when represented in conventional inner region coordinates. The location of the peak value of the temperature fluctuations is not affected by curvature, when represented in inner region coordinates. The inner layer t' and v' spectra are essentially the same in flat and curved boundary layers.

The turbulent Prandtl number appears to be the principal vehicle whereby concave curvature affects the heat transfer rate. Using a hydrodynamic model which accurately predicted the velocity profiles, we found it necessary to use a turbulent Prandtl number model which varied with streamwise distance into the curve. The turbulent Prandtl number increased in both the inner region (y+ less than 10) and the outer region (y+ between 100 and 1000) compared with the flat plate values, and the increase was more pronounced further around the curve.

We have developed a turbulent Prandtl number model which works for our data, though its generality has not been tested. This model is purely heuristic but, since it does result in good predictions it cannot be far from correct for this range of parameters.

A second objective was to learn how to predict heat transfer events in an air-flow situation based on heat transfer data from a water-flow situation, and how to interpret events seen in a water study insofar as they might carry over to air. The intent here is to make it possible to run meaningful heat transfer tests on water tunnel models now used only for fluid mechanics experiments.

Conventional correlations developed semi-analytically use a simple, multiplicative Prandtl number correction term (i.e., Prandtl number to some power) multiplied onto a Reynolds number term to describe the heat transfer and purport to be able to account for different fluids by this means. Our present results have shown that air data and water data cannot be brought into coincidence by such simple correlations. One may be able to accomplish this goal by acknowledging an effect of the Prandtl number on the Reynolds number coefficient and an effect of the Reynolds number on the Prandtl number exponent, but it is not simple.

Numerical experiments using the Stan6 boundary layer code showed that the water boundary layer could be accurately predicted using the same mixing length distribution and turbulent Prandtl number distribution used for air calculations, simply installing the physical properties of water.

Based on Hollingsworth's boundary layer study, it appears that water tunnel experiments cannot be directly used to predict air heat transfer using a simple Prandtl number shift, if accuracy of better than +/- 10% is needed even for situations involving attached boundary layers, let alone flows with separation. Water tunnel results can be used to study hydrodynamics, as has long been done, and to investigate heat transfer behavior through the intermediary of a boundary layer code such as Stan6, but heat transfer results from a water tunnel test cannot be directly converted into air results by a simple Prandtl number shift. One corollary of these findings is that analog methods of determining heat transfer using tracers, adjusted with a simple Schmidt number corrector (e.g., electrochemical or napthalene sublimation methods), cannot be relied upon with as much confidence as previously believed.

A new liquid crystal panel was built for use in the water tunnel, to examine the distribution of heat transfer coefficient under separating and reattaching flows. The intent was to see whether or not the images from the hydrodynamic and thermal events were similar in appearance when the important features of the flow were significantly far from the wall.

Three flow situations were investigated: the separation region upwind of a slanted, forward facing step, the region around an array of cubical obstructions, and the region downstream of a half-delta vortex generator. The surface heat transfer was made visible using a variant of the techniques developed by Simonich and Moffat in which an electrically heated film was coated with liquid crystal material, protected from the water by a transparent sheet. Images caused by temperature variations on the liquid crystal were processed through a digital signal processor to show the distribution of h, the heat transfer coefficient.

The liquid crystal images showed the paths of heated fluid particles, which in some respects are the thermal equivalent of stream lines. The thermal stream line images were qualitatively different from hydrodynamic images generated in the same flow field by dye injection into the sublayer. For example, in the flow field upwind of the slanted, forward facing step, the thermal images showed no sign of a separation line: the thermal streaky structure passed smoothly over the region where hydrogen bubbles indicated the separation line to be. This suggests that the information in the thermal images has a different significance from the flow lines: the thermal lines were determined mainly by the flow in the sublayer region, with little influence from events in the outer layer. Based on these observations it seems likely that thermal visualization in a water tunnel will not be a good predictor of heat transfer in air. There is also a caution here concerning the interpretation of thermal streaky structures in such experiments: they clearly do not have the same meaning as the streak lines in a bubble photograph, and their interpretation needs clarification.

Quantitative analysis was done only on the vortex generator flow. There, we showed a max-to min variation of only 7-15% in h, compared with a 35% difference in an earlier study done in air[3]. Typical results are shown in Figure 1, a plot of the ensemble averaged Hue Angle (a measure of temperature) as a function of spanwise position. The variation shown in Figure 1 corresponds to about 12% variation in h across the span shown. It appears likely that any proposals to study heat transfer in water using embedded vortical structures or separations should begin with a qualification set of experiments to quantify the relationship between air results and water results. The present set do not suffice for that calibration, since we were not able to scale the Reynolds numbers.

Partly as a result of these qualitative studies which indicated reason to doubt the interpretation of heat transfer tests in the water tunnel, the remainder of the extension work was shifted to a high turbulence air tunnel previously used in gas turbine heat transfer research. The tunnel chosen uses a simulated gas turbine combustor to generate large scale, high intensity turbulence (15.1%, uniformly across the channel at x=0.48 m, with an auto-correlation length scale of 6.22 m) in a relatively large test section (25.4 cm high, 50.8 cm wide, and 2.4 m long). The lower surface of this test section is a segmented flat plate, instrumented for heat transfer measurements. A significant body of data has been accumulated in this tunnel, concerning the effects of high turbulence on heat transfer and the turbulence properties of the flow are well documented.

Using this flow field as a base, we investigated the effect on heat transfer of changing the maximum possible normal length scale of the turbulence by abruptly decreasing the passage height, at constant velocity. This is the situation found in the first stage nozzle ring of a turbine, where the flow leaves the transition liner with large turbulence length scales (set by the dimensions of the combustor and transition liner) and enters the first stage vane passages, where the passage size is set by the vane spacing.

To create this situation, a thin splitter plate, shown in Figure 2, was installed parallel to the heat transfer surface, 8.5 cm above the surface in one series of tests and 3.8 cm above in the other, extending from x=0.81 m. to x=2.00 m. Heat transfer coefficients were measured along the full length of the surface for two free-stream velocities: 6 m/s and 12 m/s. The splitter was expected to abruptly reduce the scale of turbulent events beneath it, as suggested in Figure 3.

The experiment produced surprising and interesting results from both the hydrodynamic and the heat transfer viewpoints:

> Both splitter plates, at both velocities, caused the autocorrelation length scale measured under the splitter (at x=1.1 m) to increase, not decrease. relative to their values upwind of the splitter. The length scales went from 6.12 cm ,with no splitter, to about 7.65 for the 8.5 cm splitter and 9.86 cm for the 3.8 cm splitter. It is as though a roughly-constant-volume structure were being extruded by its confinement inside the small passage.
>
> Neither splitter plate, at either velocity, caused a significant change in the heat transfer coefficient distribution. The heat transfer behavior was substantially the same as though the splitter plates had not been there, as shown in Figure 4. The reduction in St at large X is attributed to the establishment of nearly fully developed channel flow beneath the splitter, and the magnitude of the drop has been successfully predicted based on that model.

These results suggest that there is much to be learned about the interaction of large-scale free-stream turbulence and small scale passages, as it affects heat transfer. This appears to be the first time that the "entry region" of turbulence accommodation to its passage has been studied. There are many changes in passage size within an engine and it now appears important to understand the way turbulence developed in one passage adjusts when the passage changes size.

An informal report has been written to document these results[4] and a technical note is in preparation for publication.

3.2 Studies of Wake-Like Turbulence Interacting with Turbulent Boundary Layers (Bradshaw)

In the present research we have so far concentrated on spatial inhomogeneity (within blade stages), restricted to fairly low turbulence intensities: the work of Moffat et al. is concerned with nominally-homogeneous, high-intensity effluxes from combustion chambers.

The flow into a given blade row (not too near the inlet from the combustion chamber) consists of low-speed turbulent wakes of upstream blades, plus high-speed, low-turbulent flow between blades. Thus it is a combination of spatially-periodic "ordered unsteadiness" and genuine (but again spatially-inhomogeneous) turbulence. As we have reported before (e.g. Baskaran and Bradshaw, paper presented at 7th International Symposium on Turbulent Shear Flow, Stanford, 1989), Schwarz's inequality shows that periodic unsteadiness increases the time-average dynamic pressure for a given time-average velocity (mass flow rate), and increases drag for this simple reason, independent of the turbulence.

Previous investigations of blade "turbulence" generated by moving arrays of parallel bars are thus almost worthless. The effects of spatial inhomogeneity of the genuine turbulence need investigating independently of ordered unsteadiness.

Our current work concerns spatially-inhomogeneous turbulence in the absence of mean-velocity variations, generated by a graded grid which produces a turbulence intensity of the order of 10% on the top half of the grid and a negligibly low turbulence intensity on the top half of the grid. We are measuring heat-transfer parameters and joint statistics of temperature and velocity fluctuations, as well as the velocity field as such.

The turbulent flow from the upper part of the grid diffuses downwards and spreads into the boundary layer of the upper surface of a flat plate in the working section, like the turbulent part of the wake of an upstream blade. Development of such a dual grid is not easy because the requirements of continuous total-pressure loss and discontinuous turbulent energy production are strictly incompatible.

4. PUBLICATIONS for the period Jan. 1, 1989 through Dec. 31, 1990.

Baskaran, V., Abdellatif, O.E., and P. Bradshaw (1989), "Effects of free-stream turbulence on turbulent boundary layers with convective heat transfer," 7'th Symposium on Turbulent Shear Flows, Stanford University, Aug. 21-23, 1989, pp 20.1.1 - 20.1.6.

Baskaran, V., P. Bradshaw (1989), "An experimental study of a wake-boundary layer interaction," Australasian Fluid Mechanics Conference, Melbourne, 1989.

Hollingsworth, D. K., W. M. Kays, and R. J. Moffat (1989a), "Measurement and Prediction of the Turbulent Thermal Boundary Layer in Water on Flat and Concave Surfaces," Report No. HMT-41, Thermosciences Division, Mechanical Engineering Dept., Stanford University, Sept. 1989, 199 pages.

Hollingsworth, D. K., W. M. Kays, and R. J. Moffat (1989b), "Measurement and Prediction of the Turbulent Thermal Boundary Layer in Water," 7'th Symposium on Turbulent Shear Flows, Stanford University, Aug. 21-23, 1989, pp 20.4.1 - 20.4.5.

Johnson, P. L. and R. S. Barlow (1989), "Effects of measuring volume length on two-component laser velocimeter measurements in a turbulent boundary layer," Experiments in Fluids, vol. 8, 1989, pp 137-144.

Johnson, P. L. and J. P. Johnston (1989a), "The Effects of Grid-Generated Turbulence on Flat and Concave Turbulent Boundary Layers," Report No. MD-53, Thermosciences Division, Mechanical Engineering Dept., Stanford University, Nov. 1989, 247 pages.

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Johnson, P. L. and J. P. Johnston (1990), "The Effect of Streamline Curvature on Decaying Grid Turbulence," 12th Symposium on Turbulence, Sept. 24-26, U. of Missouri, Rolla, MO.

5. PROFESSIONAL PERSONNEL (in addition to the principal investigators)

Research Assistants:

Millicent Coil - Masters student
Started: July 1989
MS awarded: December 1990

Thomas J. Feiereisen - Post Masters student,
Started: January, 1990
Transferred out: September, 1991

Donald K. Hollingsworth - Ph. D. awarded in December, 1989.
Dissertation title: "Measurement and Prediction of the Turbulent Thermal Boundary Layer in Water on Flat and Concave Surfaces."

Paul L. Johnson - Ph. D. awarded in December, 1989.
Dissertation title: "The Effects of Grid-Generated Turbulence on Flat and Concave Turbulent Boundary Layers."

Paul Malan - Post Masters student,
Started: January, 1990

6. INTERACTIONS

P. Bradshaw - Visit and consultation at Pratt & Whitney and United Tech. Research Center 1989; lecture course at United Tech. Research Center 1990; discussions of cascade tests with Pratt & Whitney representatives 1989 - 1991.

R. J. Moffat - Two full days of discussion, at Stanford, with representatives of major US aircraft engine manufacturers (United Technologies; Pratt and Whitney; Allison Division, General Motors Corp; and Textron Lycoming) regarding heat transfer on concave surfaces with and without high turbulence. These discussions took place as an adjunct to the annual meeting of the Thermosciences Affiliates and Sponsors, a group of high-technology industries who support research in the Thermosciences Division.

Pratt and Whitney/United Technologies: August '89, a. seminar on turbine blade and vane cooling and high temperature measurements.

Textron-Lycoming: August, '89, seminar on heat transfer in gas turbines and experimental techniques for testing high temperature heat exchangers.

Caterpillar Tractor: August, '89. Discussions on experimental techniques relating to heat transfer measurements in combustion chambers and on gas turbine components.

7. NEW DISCOVERIES - none for the period except those mentioned in the summary reports above - the results of our research.

References

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[1] Hollingsworth, D. K. , Kays, W. M., and Moffat, R. J. "Measurement and Prediction of the Turbulent Thermal Boundary Layer in Water on Flat and Concave Surfaces" Thermosciences Division Research Report HMT-41, Stanford University, 1989.

[2] Simonich, J. C., and Moffat, R. J. "Local Measurementds of Turbulent Boundary Layer Heat Transfer on a Concave Surface Using Liquid Crystals" Thermosciences Division Research Report HMT-35, Stanford University, 1982.

[3] Feireisen, T. and Moffat, R. J. "An Experimental Investigation of the Spanwise Surface Heat Transfer Coefficient Behind a Vortex Generator in Water" Thermosciences Division Research Report, IL-110, 1991.

[4] Batchelder, K., Campbell, R. and Moffat, R.J. "The Effect of an Abrupt Reduction of Passage Height on Heat Transfer with High Free-Stream Turbulence" Thermosciences Division Research Report, IL-111, 1991.

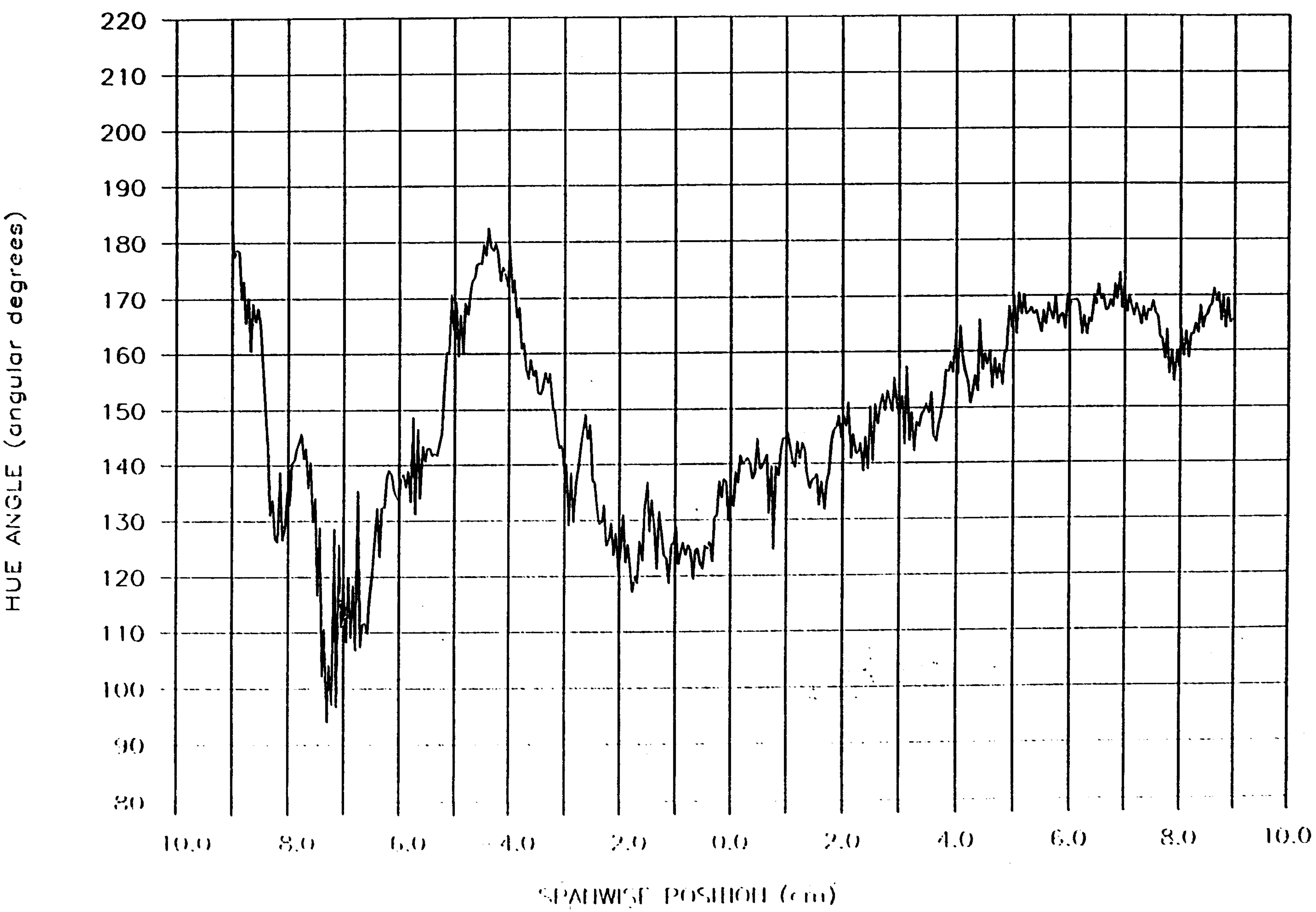

Figure 1. Ensemble average of hue angle across the liquid crystal panel, vortex generator mounted 24 cm upstream, panel heat flux = 0.46 W/m^2

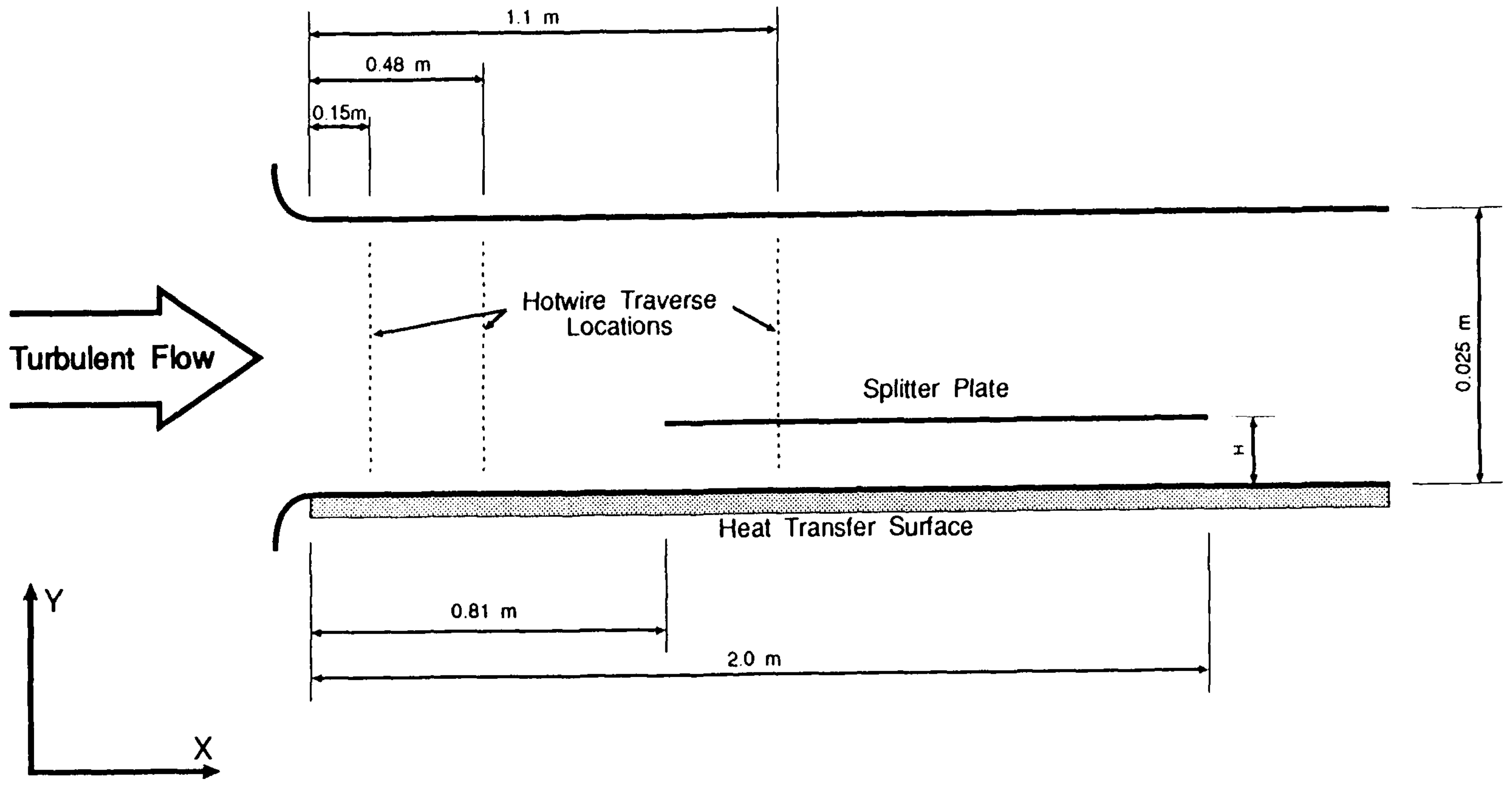

Figure 2: Schematic of wind tunnel with splitter plate installed

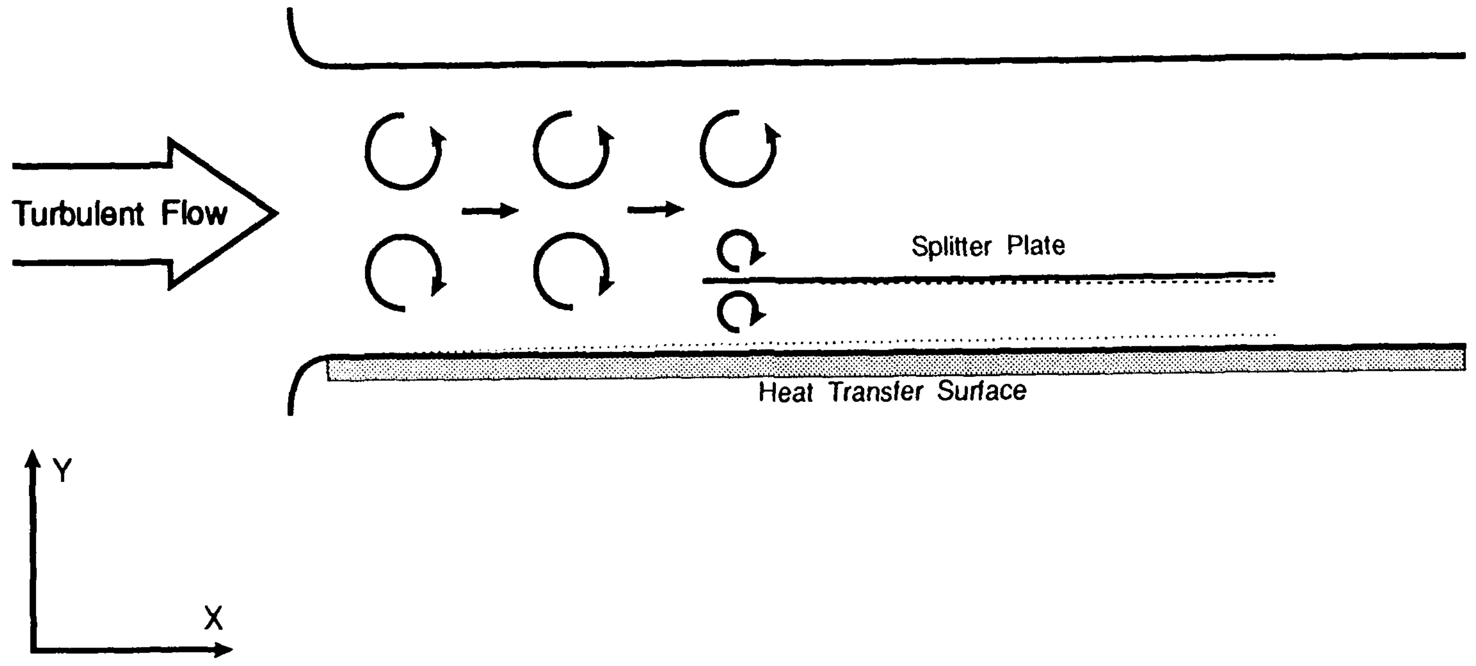

Figure 3: Hypothesized effect of splitter plate on turbulence length scales

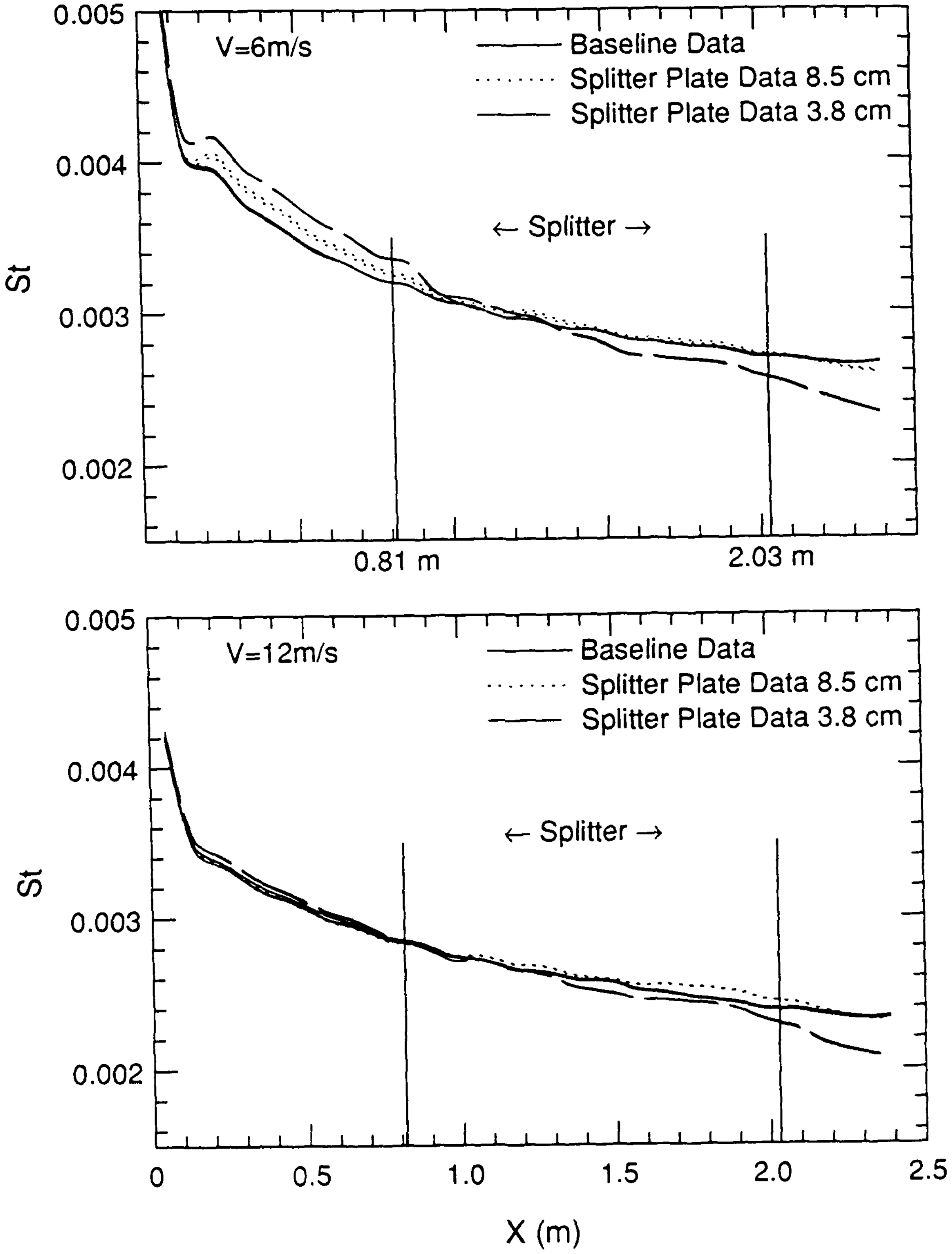

Figure 4: Heat transfer results compared to baseline data