AERODYNAMICS

CONTROL OF SURFACE SHEAR STRESS FLUCTUATIONS

IN TURBULENT BOUNDARY LAYERS

by

V. A. Sandborn

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ABSTRACT

an experimental study of techniques for modifying the surface
shear stress, both mean and fluctuating, in turbulent boundary
layers is reported. The surface shear along the test section of a
45.7cm square wind tunnel, with a downstream expansion section, was
determined by means of surface-hot-wire-heat-transfer-gauges.
Turbulent boundary layers in both zero and adverse pressure gradients
were evaluated.

The mean and fluctuating surface shear in a zero pressure
gradient can be effectively reduced by employing a set of closely
spaced fins. The fins protruded from the surface up through the
sublayer. The fins produced an effective momentum defect for the
boundary layer near the surface, which reduced the surface shear
fluctuations by as much as 75 percent, two boundary layer thick-
nesses downstream, and 52 percent 15 boundary layer thicknesses
downstram (the limit of the present experiment). The mean surface
shear was also reduced by 35 to 25 percent for the same 2 to 15
boundary thicknesses downstream. The fins do not appear to
produce a large increase in the thickness of the layer.

No small size device, which could be mounted in the sublayer,
was found that could develope a persistent increase in either the
mean or fluctuating surface shear. Small scale vortex generators
had no measurable effect on the flow for downstream distances
greater than approximately 4 to 5 boundary layer thicknesses.
Only the large scale vortex generator, normally use to delay boundary
layer separation, produced an increase in surface shear at large
distances downstream.

INTRODUCTION

Control of both the mean and fluctuating surface shear in turbulent
boundary layers can be of value in a large number of fluid flow problems.
Reduction of the mean surface shear in zero pressure gradient flows could
reduce the amount of energy required to move ships or aircraft through the
fluid. Reduction of the fluctuating surface shear will have a direct effect
on the noise generated by the boundary layer. Also the reduction of the
fluctuating surface shear in rivers will reduce the movement of sediment.

At the other extreme, increasing the surface shear will delay the separation of the turbulent boundary layer in an adverse pressure gradient.

Modification of the surface shear in turbulent boundary layers is not a new concept. Snow fences are a direct attempt to reduce the shear, in order to keep the snow from covering passage ways. Blowing and suction are also methods of modifying the boundary layer, which in turn modify the surface shear. Large scale vortex generators are employed to delay turbulent boundary layer separation, which may be viewed as increasing the surface shear in the adverse pressure region.

The present study employed a surface heat transfer gauge as a direct means of evaluating the effect of a number of devices on the surface shear. The gauge can indicate both the mean and fluctuating components of the surface shear. Both zero- and adverse-pressure gradient flow was employed for the study.

EXPERIMENTAL SETUP

The experiments were made in a small, 45.7 x 45.7 cm, open return wind tunnel, figure 1. The test section consisted of a near zero pressure gradient region of 190 cm in length. The turbulent boundary layer was approximately 6.4 cm in thickness, and a momentum thickness Reynolds number of 4050 was developed at the measuring station for a freestream velocity of 10.2 m/sec. The static pressure distribution along the centerline of the test surface is shown in figure 2. For the zero pressure gradient studies a surface-hot-wire was located at x = 198 cm. A detailed evaluation of the flow at this location is given by Chien and Sandborn (1981). For the adverse pressure study a surface-hot-wire located at x = 250 cm was used to indicate changes in the surface shear. Since the present study was of an exploratory nature, most of the tests were made at a freestream velocity of 10.2 m/sec. Only for one set of fins was the effect of Reynolds number explored.

Surface Shear Measurements.- The surface shear was evaluated from surface heat transfer measurements made with hot wires mounted directly on the surface, Sandborn (1981). Platinum-8%tungsten alloy wire, .001 cm in diameter and approximately 0.13 cm long were mounted directly between copper conductors imbedded in a plastic surface, figure 3. The wires are layed directly on the surface, but are not physically attached except at their ends. The use of buried wires are not desirable, since their frequency response to the surface fluctuations is limited. Film gauges were not used, since their effective length in the flow direction is large. The hot wire sensors were built on the special insert plugs, shown on figure 3. The plastic polymide surface was employed to reduce the heat transfer into the substrate. The plastic material was also black in color, which greatly facilitates the mounting of the surface wires.

The transfer function between the measured surface heat transfer and the surface shear was obtained from evaluation of the boundary layer velocity profiles measured at the location of the sensor. A number of emprical relations exist for surface shear or skin friction coefficient as a function of the velocity profile-momentum thickness Reynolds number for zero pressure

gradient turbulent boundary layers. Figure 4 is a plot of the local skin friction coefficient, c_f, as a function of momentum thickness Reynolds number. Relations for c_f, reported by Granville (1975), Prandtl (1927), and Bell (1979) are also plotted on figure 4. A second relation obtained by Bell (1927), which includes a second velocity profile parameter, form factor H, is also shown on figure 4. Typical measured values of R_θ and H measured in the present study are plotted on the two parameter relation given by Bell. Between the different c_f relations shown there is roughly a ±3% variation in the values of c_f. At the present time it is doubtful that the accuracy of c_f can be obtained to better than ±3% for the low velocity flows considered.

The large fluctuations of surface shear encountered in the zero pressure gradient turbulent boundary layer, produce a non-linear error in the calibration between the surface-heat transfer and-shear. A special technique outlined by Sandborn (1979) was used to correct the calibration for the non-linear averaging. In order to reduce the calculation time an approximate relation was used to evaluate the surface shear for the measurements behind the different devices. The transfer function between the mean surface shear, $\overline{\tau}_w$, and the output voltage of the hot wire (operating in a constant temperature anemometer circuit) is assumed to be of the form, Sandborn (1972)

$$\overline{\tau}_w = \overline{[A(E + e)^2 + B]^3}$$ (1)

where E is the hot wire mean voltage output and e is the time dependent voltage perturbation about the mean value. Taking the mean of the left hand side of equation (1) results in terms containing $\overline{e^2}$, $\overline{e^3}$, $\overline{e^4}$, $\overline{e^5}$ and $\overline{e^6}$. It is assumed that all of the higher moments of the perturbation voltage appear in terms that are small compared to the $\overline{e^2}$ terms. Thus, equation (1) is approximated as

$$\overline{\tau}_w \approx AE^2(A^2E^4 + 3ABE^2 + 3B^2) + 3A\overline{e^2}(2A^2E^4 + 4ABE^2 + B^2) + B^3$$ (2)

For each measured value of E and $\overline{e^2}$ a value of $\overline{\tau}_w$ was computed. The values of A and B were determined from the corrected transfer function. The approximation appears to give values of $\overline{\tau}_w$ within ±5% of values obtained by the more complex evaluation reported by Sandborn (1979). Repeat calibrations of the surface hot wire transfer function were found to vary by approximately ±4%, so the use of equation (2) does not appear to produce a measurable error. The fact that the hot wire is not extremely sensitive to surface shear (i.e. $\overline{\tau}_w \propto E^6$) helps to reduce the non-linear effects. The measurements are presented as a ratio to the undisturbed shear, which was obtained independently from velocity profile measurements. For each ratio the hot wire measurement with and without the shear modification device in place was used. Thus, it was possible to correct for slight variations in the sensor

sensitivity due to small changes in flow temperature. Some uncertainty
may exist in the measurements, due to the presence of local pressure
gradients induced by the flow modification devices.

The ratio of the fluctuations with and without the modification
devices was computed assuming a local linearization of the transfer
function, Sandborn (1972). Since the surface hot wire is not highly
sensitive to the surface shear, the error due to local linearization
(replacing the transfer function by its local slope) is quite small (see
the evaluation of hot wire anemometer errors given by Sandborn (1972)).
The main error in evaluating the fluctuations is associated with the
accuracy of the transfer function. Individual evaluations of the fluctu-
ating surface shear are uncertain by approximately ±5%, although the
accuracy of the ratios should not have nearly as high an uncertainty.
For the present exploratory study both the mean and fluctuating voltages
were measured with long time averaging analog volt meters.

Flow Modification Devices. - A number of devices have been tested
as possible ways of increasing or decreasing the mean and fluctuating
surface shear. A large number of different size fin sets were tested to
determine possible trends toward an optimum geometry. Thin ribbons or
plates placed parallel to the surface were employed in the basic study
of the fluctuating surface shear. The results for thin plates near the
surface are given in the companion report, Chein and Sandborn (1981).
Some information on larger, thin plates, placed in the outer region of
the boundary layer was obtained in the present study. Cylinderical rods
placed both on the surface and at slight distances above the surface was
included in the study. A thin airfoil with trailing edge blowing was
also evaluated. Flexable strips, and solid and open fences were evaluated
as possible devices for increasing the surface fluctuations. A number of
different sizes and shapes of vortex generators were also evaluated. Sizes
and construction details for the devices are given in Table I.

RESULTS AND DISCUSSION

Zero Pressure Gradient Flow.-(FINS) Of the many devices tested the
sets of closely spaced fins and the flexable elements were the most effective
in reducing both the mean and fluctuating surface shear for the zero pressure
gradient flow. Figure 5 shows typical variations of the mean and fluctuating
surface shear ratios obtained by placing the sets of fins at various distances
upstream of the surface hot wire sensor. The closely spaced (S = 0.26cm) set
of fins produce nearly a 30% reduction in the mean surface shear and a 50% in τ'_w
reduction at a distance of 90cm upstream of the sensor. This upstream distance
is equivalent to 14.6 boundary layer thicknesses of the undisturbed flow
at the hot wire location. Figure 6 shows measurements for a series of small
sized fins. The smaller fins produce a pronounced effect at short distances
upstream, but there reduction in the surface shear does not persist for as
great a distance as that of the large fins.

The velocity distributions at the measuring station with the S =0.26cm spaced fins (figure 1) set at 20cm and 90cm are shown on figure 7. The fins produce a large momentum defect in the boundary layer near the surface. Smoke visualization directly down stream of the fins did not indicate a region of separation, although the very large drop in mean shear directly behind the fins would suggest a near separating condition. Directly behind the fins the surface shear fluctuations are nearly non-existant. The values of the fluctuating shear plotted near x = o are questionable, as they are approaching the noise level of the anemometer system.

As noted on the insert of figure 5, the alignment of the fins with the mean flow was not critical. A variation of 15 degrees from the mean flow direction produced practically no change in the mean shear value The insensitivity to slight flow angles should be of great value. It was demonstrated by Chien and Sandborn (1981) that the misalignment of the thin plates had a major effect on the surface shear.

Figure 8 is a review of the information obtained to date on the effect of fin-spacing, width and span. For the present boundary layer, fin spacings of the order of 0.1cm would appear to produce the maximum reduction in both the mean and fluctuating surface shear. For direct drag reduction applications there may be a trade off between the spacing and the form drag of the fins. The width of the fin has not been evaluated sufficiently to make a definite statement on the optimum. Likewise the height of the fins need to be investigated further. The present study has also been limited to finite span of the fin sets. Figure 8c) suggests that the results are not critical for spans equal to or greater than the boundary layer thickness.

The effect of Reynolds number was investigated for the 0.26cm spacing fin set (figure 5). Figure 9 shows the measurements for R_θ = 4050, which were also plotted on figure 5, compared with measurements at R_θ = 3080. The percentage reduction in the mean shear is not as great for the lower Reynolds number flow as for the higher Reynolds number flow. The reduction in the fluctuating shear is approximately the same for both Reynolds numbers.

Zero pressure gradient flow. - (Other devices) A number of devices were investigated, which produced a momentum loss and reduction in both the mean and fluctuating surface shear. As noted previously, the use of thin plates, or ribbons near the surface was investigated in detail and the results are contained in the companion report Chien and Sandborn (1981). A number of other possible thin plate configurations, such as two plates in tandem were also investigated. The different thin plate configurations and the indicated shear are tabulated in Table II. In general the two plates in tandem produce a larger local reduction in the surface shear than a single plate, however, the effect persists for a very short distance downstream. As noted in the report by Chien and Sandborn (1981), the plates block the large fluctuation in surface shear from reaching the surface, but they do not alter the production of the large pulses.

In a private communication with the research group at Illinois Institute of Technology it was pointed out that they were modifying the large scale structure of the boundary layer by the use of thin plates placed in the outer region of the layer. Based on the limited information obtained, a series of single and tandem, thin plates were tested in the outer part of the boundary layer. The results of these tests are also included in Table II. While a reduction in surface shear was noted for the outer region plates, the reduction was much less than that observed for either the plates near the surface or many of the other inner layer devices.

Figure 10 is a summary of tests made with a number of different devices: solid fence, open fence, flexable elements, rods on the surface, rods above the surface, jet blowing airfoil, sublayer vortex generators and a large scale vortex generator. Most of the devices show similar characteristics of a large increase in the mean or fluctuating surface shear directly down-stream. In one or two boundary layer thicknesses downstream the mean and fluctuating surface shear drops off to values usually less than the base flow value. By four or five boundary thicknesses, the effect of the device on the surface shear is usually quite small. The most surprising result was that the large fluctuation generators, such as the rods above the surface, actually reduce the surface shear fluctuation once they are one boundary layer thickness upstream. It became evident that generation of fluctuations in the sublayer will not persist for any great length downstream.

The flexible element device (figure 10a) was a series of thin plastic strips glued to the surface and bent so they were vertical for no flow. The strips were 2.6cm high (.4 of boundary layer thickness) and between .1 and .2 wide. They were free to bend backward in the flow. The device was not investigated until late in the study, so only a limited amount of data was obtained. Originally it was assumed that the flexable strips would act as turbulence generators rather than dampers. Obviously the strips are acting more as a compliant surface. The flexáble elements should be further investigated as a means of reducing the surface shear.

The small vortex generators, shown on figure 10e), were able to increase the surface shear over short distances only. The devices were designed to produce the high and low velocity jets similar to the sweep-burst phenomenon observed in natural boundary layers. It was thought that the high velocity jets would produce a low pressure, which in turn would pull flow from the outer region of the layer inward. Unfortunately, the effect is not able to generate sufficiently large mixing to persist for more than a few boundary layer thicknesses. It may be worthwhile to investigate the small vortex generators further, and also to consider then in conjunction with the large scale generator.

It was found that the large scale vortex generator had no effect on the local surface shear until it was at least six boundary layer thicknesses up-stream.

Adverse pressure gradients. - The pressure gradient for the test surface is shown in figure 2. The adverse pressure gradient region was proceeded by a strong favorable pressure gradient. Details of the velocity distribution in the adverse pressure region are given in Appendix A. An intermittent separation was indicated at x = 266cm and a zero-surface-shear stress occurred at about x = 273cm. In order to evaluate the effect of vortex generators on the surface shear near separation, a surface hot wire sensor at x = 250cm was employed. Figure 11 shows the indicated change in surface shear produced by a number of vortex generators and deflector plates. The large scale vortex generator mounted far upstream in the zero pressure gradient region produced the largest effect (8%) on the mean surface shear. The large scale vortex generator also increased the surface shear fluctuations by 20 to 36 percent. The small scale vortex generators were unable to increase the surface shear by more than 1 or 2 percent, and they actually decreased the fluctuations. Defector plates set parallel to the ramp gave roughly the same magnitude of effect as the large vortex generator.

The particular flow studied is perhaps too severe in both the favorable and adverse pressure gradient regions. A flow with milder conditions might be a better test of devices for the delay of separation.

CONCLUDING REMARKS

The present study demonstrates the value of the surface hot wire-shear gauge in evaluating the effect of modification devices. Devices, such as rods, were thought to produce effects that last for long distances downstream. Measurements of the velocity profiles and turbulence would suggest that many boundary layer thicknesses are required for the flow to recover. The present measure of surface shear suggests that the disturbances do not persist at the wall for more than a few lengths.

The major effects of the fins in reducing both the mean and fluctuating surface shear suggest that the lateral or 3-dimensional aspects of the turbulence is important. It was observed that thin ribbons or plates could block the fluctuation from reaching the surface, but in no way do the plates alter the development of the fluctuation downstream. Thus, the fluctuations would appear to be controlled by the lateral effects. At present it is not clear just how the fins (or the flexable elements) damp the large scale surface shear fluctuations.

It was assumed that the generation of fluctuations by a number of devices would pose no problem. However, it was not foreseen that turbulence generated near the surface can not persist for long distances. Only the large scale disturbances developed by such devices as large vortex generators that extended across the total boundary layer thickness appear to be able to persist for the large distances required to delay boundary layer separation.

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TABLE I. FLOW CONTROL DEVICES

FINS
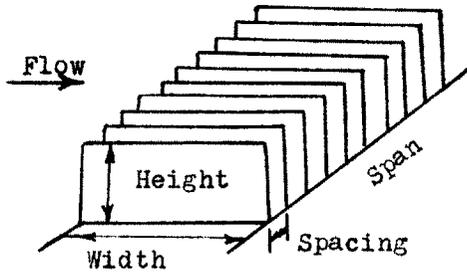
0.014 cm thick aluminum sheet used for construction. Each fin is made with a 90 degree bend at bottom of the width of the spacing. Each fin is glued to a 0.014 cm thick sheet. The sheet is in turn glued to the wind tunnel surface.
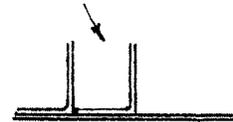
ID	width cm	height cm	spacing cm	span cm
1	3.22	1.75	.264	15.09
2	3.18	1.79	.462	21.07
3	3.190	.765	.13	11.71
4	2.591	.795	.23	19.49
5	2.596	.780	.462	21.07
6	3.18	.765	.13	2.35 to 11.7
7	2.6	.767	.45	
8	.635to3.18	.791	.168	3.05
9	2.54	.79	.102	2.54

RODS

Diameter cm	Length cm	Remarks
.122	33.3	on surface and 2 cm above
.173	33.3	on surface only
.320	33.3	on surface and 0.36 cm above

FENCES

Open

←12.7 cm→
.066 cm diameter rods
.64 cm
0.11 cm high and 0.13 cm wide

Solid

Flow
0.014 cm aluminum
0.64 cm high and 12.6 cm span

FLEXABLE ELEMENTS

←11 cm→
.15 cm wide
.01 cm thick plastic
2.6cm
.014 cm aluminum plate

BLOWING AIRFOIL

|—1.63cm—|
.190cm
.076cm slot
|—2.16cm—|
span 16.5 cm
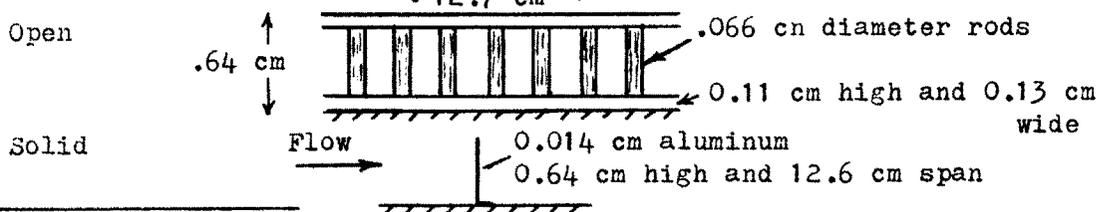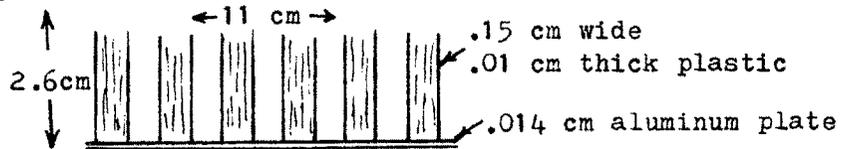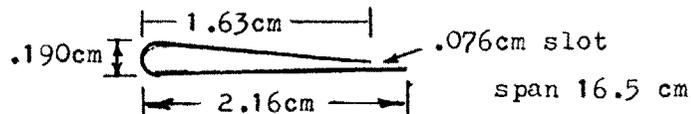
TABLE I. (Concluded) FLOW CONTROL DEVICES

VORTEX GENERATORS

1. Large scale
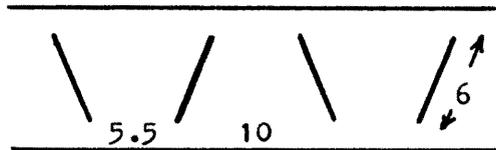
4 cm high

2. Small scale
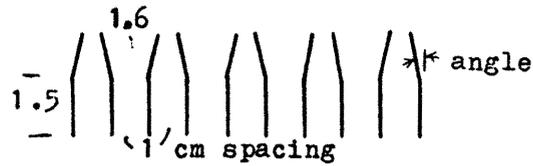
1.8 cm high

3. Small scale

1.8 cm high

4. Large scale
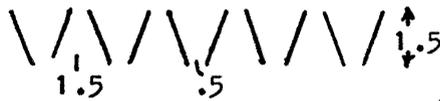
5.3 cm high

all dimensions in cm

↑ Flow

TABLE II. THIN PLATE TESTS

Flow

span

width

Thin plate

height

distance

Surface hot wire
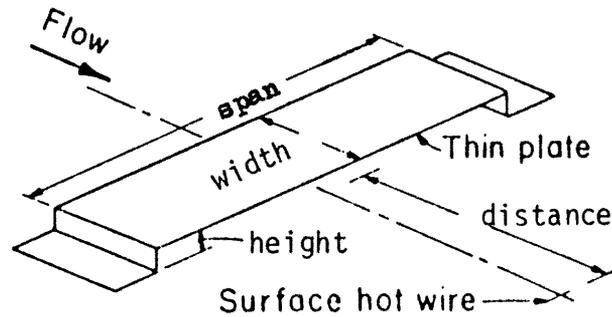
1. 5.1 cm wide, 5 cm high, 0.014 cm thick, 20.3 cm span.

Location* cm	$\overline{\tau}_w/\overline{\tau}_{w,o}$	$\tau'_w/\tau'_{w,o}$
3.6	1.00	.984
13.6	1.02	1.03
23.6	1.01	1.03

2. 5.1 cm wide, 2.6 cm high, 0.014 cm thick, 20.3 cm span.

3.6	1.03	1.02
13.6	.984	.953
23.6	1.03	1.06

3. 5.1 cm wide, 0.2 cm high, 0.014 thick, 20.3 cm span.

5.6	.564	.241
8.6	.719	.566

Two plates in tandem

4. 5.1 cm wide, 2.6 cm high, 0.014 cm thick, 20.3 cm span.

Plate 1	Plate 2		
13.6 cm	3.6 cm	1.00	.959
23.6	13.6	.918	.830
33.6	23.6	.943	.868
33.6	13.6	.950	.973
23.6	18.6	.951	.904

Note: plates are together

5. 3 cm wide, 0.014 cm thick, 12.6 cm span.

Location Plate 1	Plate2	Height Plate 1	Plate 2	$\overline{\tau}_w/\overline{\tau}_{w,o}$	$\tau'_w/\tau'_{w,o}$
8.5cm	3.5cm	0.2cm	0.2cm	.493	.062
(Plate 2 only)				.541	.130
11.5	5.5	0.2	0.2	.732	.616
(Plate 2 only)				.627	.290
8.5	3.5	0.1	0.2	.566	.165
(Plate 2 only)				.643	.245
11.5	5.5	0.4	0.2	.588	.246
(Plate 2 only)				.704	.479

* Location of center of plates upstream of sensor.

TABLE II. (Concluded) THIN PLATE TESTS

6. 0.014 cm thick, 12.6 cm span

Location		Height		Width		$\overline{\tau}_w / \overline{\tau}_{w,o}$	$\tau'_w / \tau'_{w,o}$
Plate 1	Plate 2	Plate 1	Plate 2	Plate 1	Plate 2		
7.75cm	3.5cm	0.2cm	0.2cm	1.5cm	3cm	.557	.138
(Plate 2 only)						.621	.218
8.5	2.75	0.2	0.2	3.0	1.5	.590	.246
(Plate 2 only)						.706	.358

Two plates directly above each other

7. 3 cm wide, 0.014 cm thick, 12.6 cm span, plate 1 - 0.4 cm high.
plate 2 - 0.2 cm high

Location cm	$\overline{\tau}_w / \overline{\tau}_{w,o}$	$\tau'_w / \tau'_{w,o}$
-5.5	.843	.779
-4	.792	.711
-1.5	1.04	.465
+3.5	.583	.164
5.5	.616	.247
8.5	.734	.503
11.5	.781	.563
21.5	.868	.789

Three plates directly above each other

8. 3 cm wide, 0.014 cm thick, 12.6 cm span, plate 1 - 0.8 cm high
plate 2 - 0.4 cm high
plate 3 - 0.2 cm high

3.5	.545	.216
21.5	.815	.689

13.1m

1.02m .86 .56 3.05m 6.1m

Test Section

Metal Transition

Plexiglas Section Transition Fiberglass

Fan Section

222cm 20cm

Smooth flat plate

48.8cm

Flexible curve

Adverse Pressure region
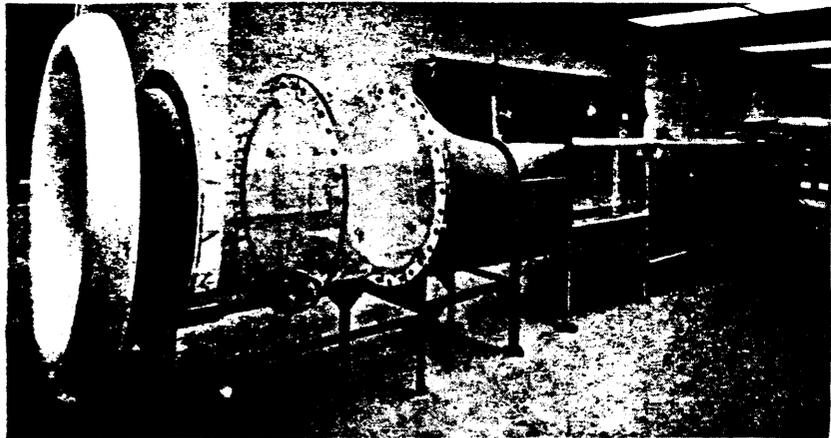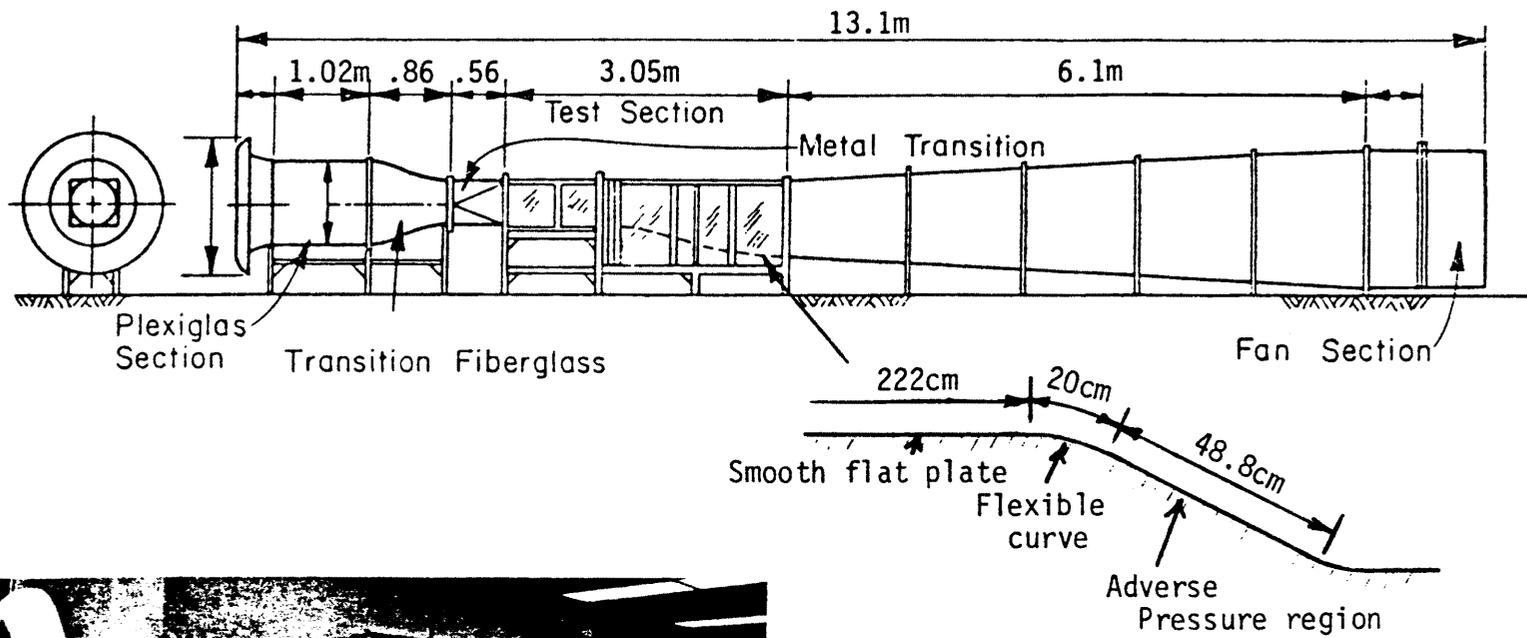
Figure 1.   Wind tunnel facilities and steup of the test section.

0.23 cm brass tube
Polymide insert

0.001 cm Diam.
Pt-8%W wire

Flow
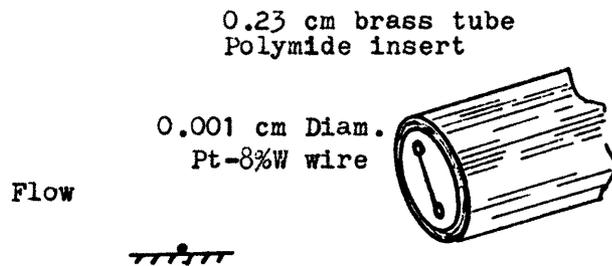
Figure 3. Surface hot wire-heat transfer sensor.

1.35
1.36
1.37

Bell, one parameter
Bell, two parameter
Granville
Prandtl

1.38

Skin Friction Coef., $c_f \times 10^3$

3.5

3.0

2.5

2   3   4   5   6x10³

Momentum thickness Reynolds No.
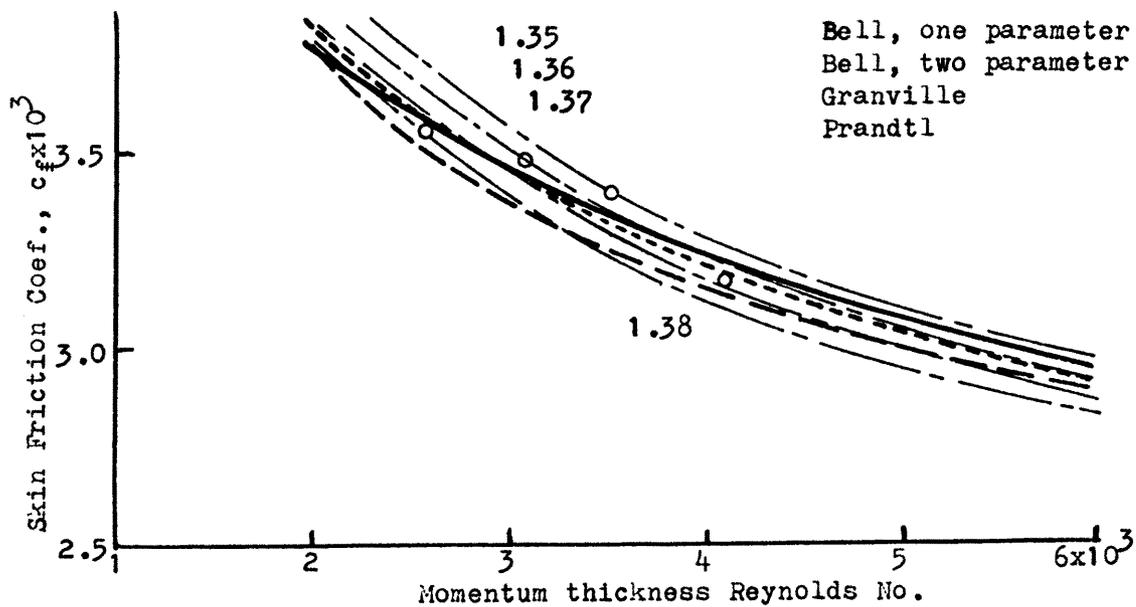
Figure 4.- Local shear stress determination.
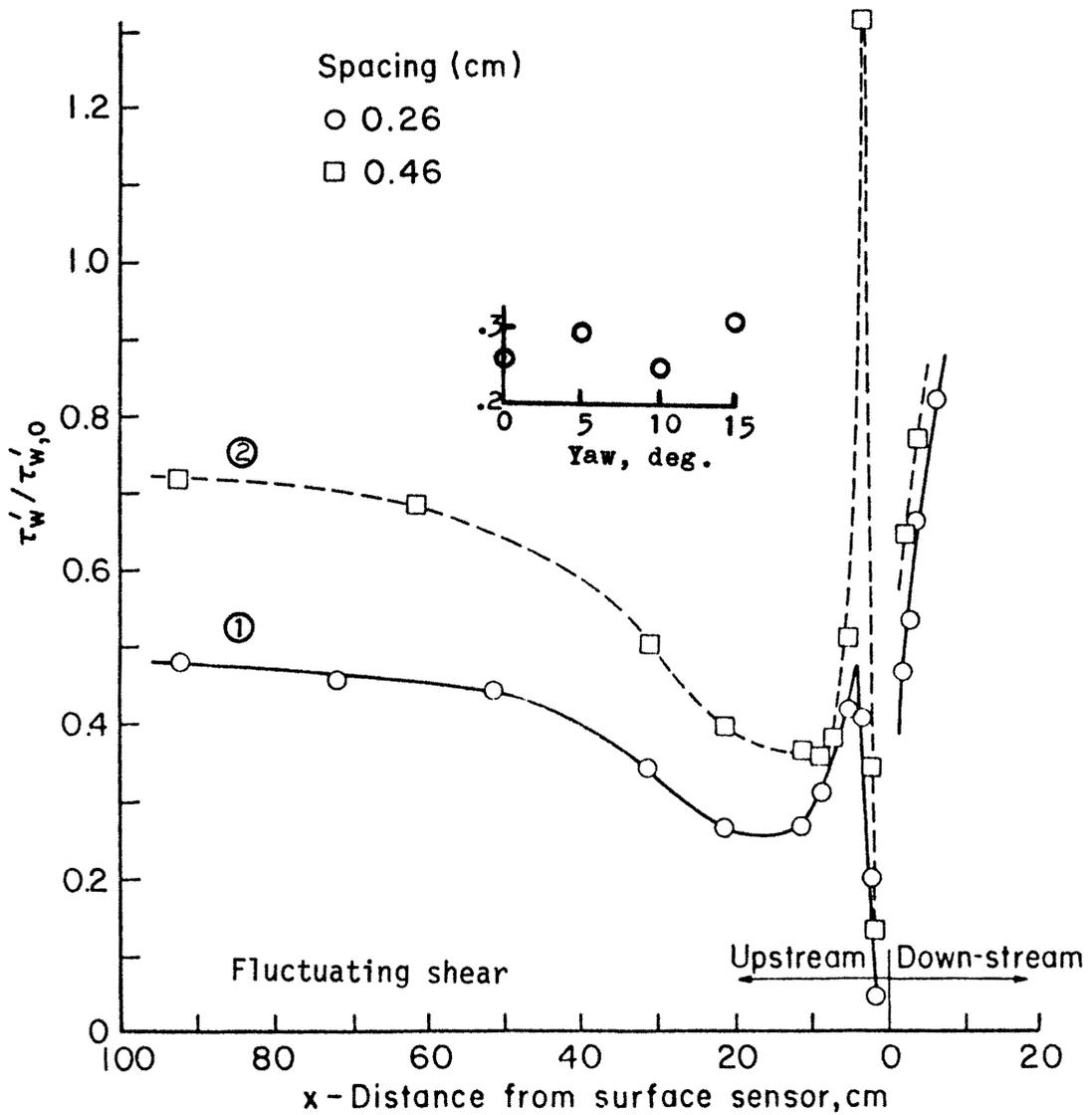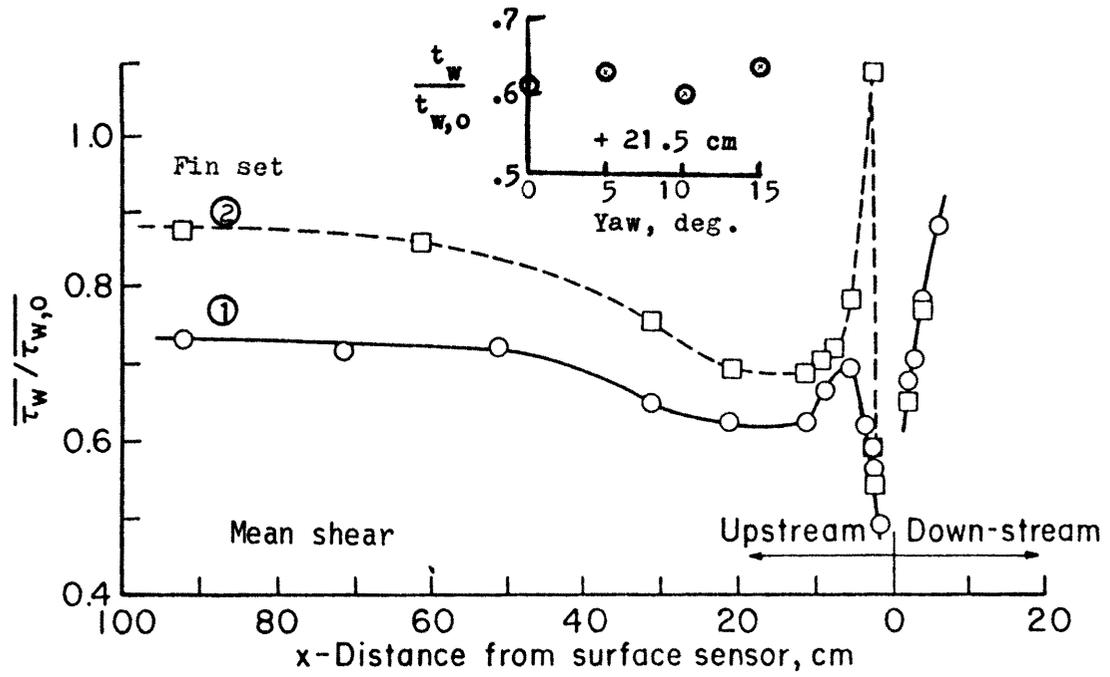
Figure 5.- Variation of the mean and fluctuating surface shear for
two sets of fins.
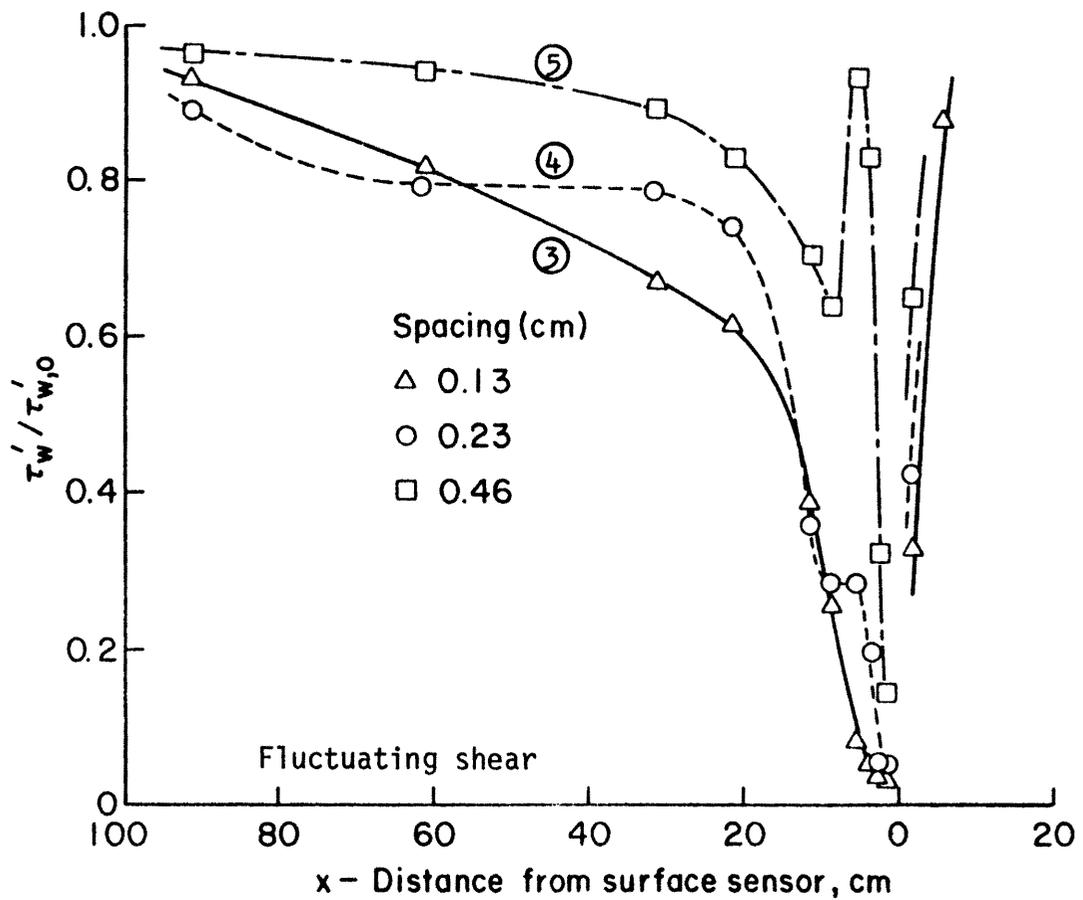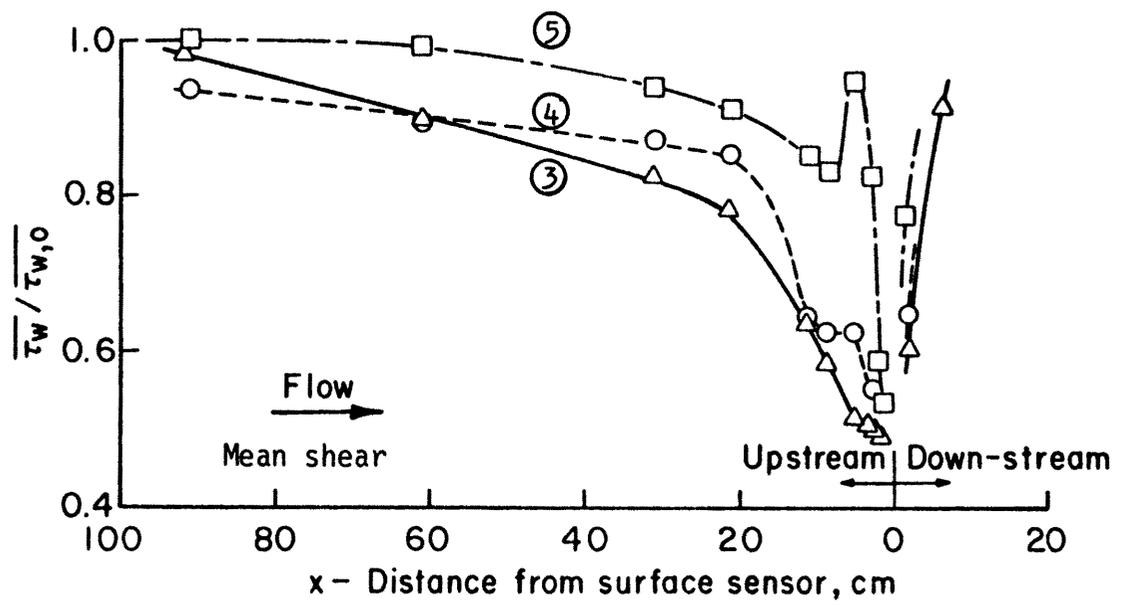
Figure 6.- Effect of small size fins on the mean and fluctuating surface shear.

		□ base	△ +20cm	○ +90cm
δ	cm	6.35	6.86	7.37
δ^*	cm	.991	1.47	1.61
θ	cm	.718	.813	1.02
H		1.38	1.81	1.58
$\tau_w \, N/m^2$		.171	.107	.125
R_θ		4050	4530	5670
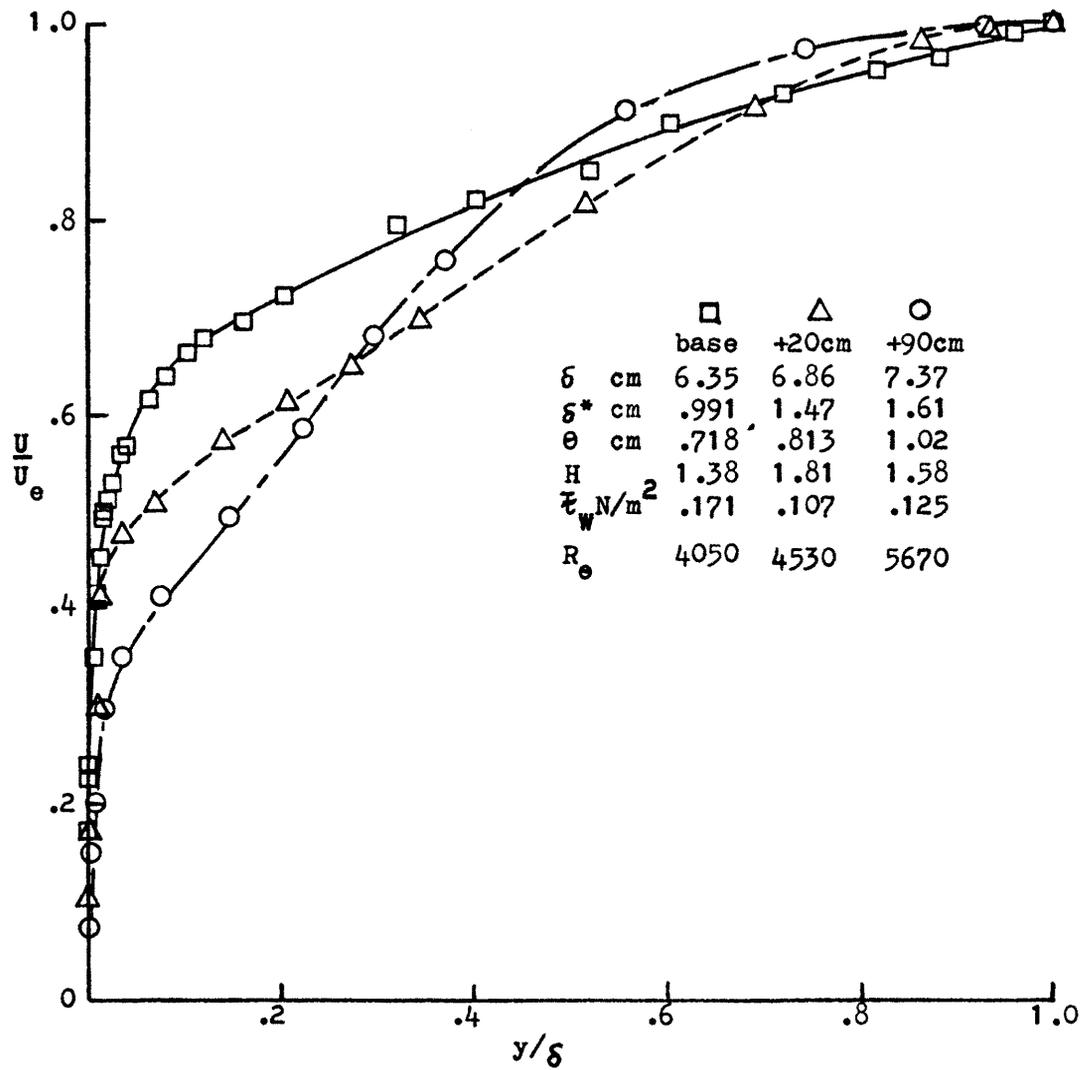
Figure 7.- Variation of the mean velocity distribution downstream of fin set number ①.
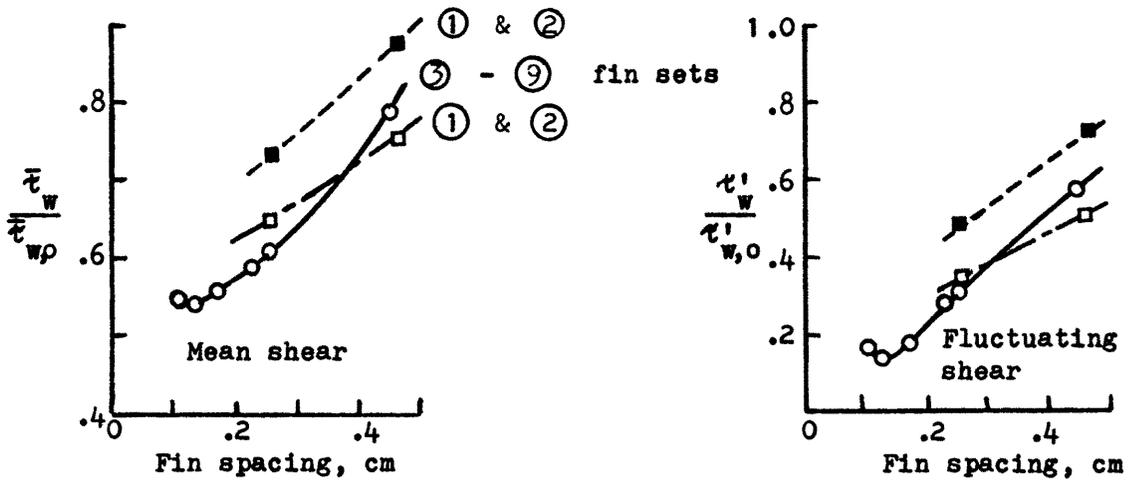
a) Effect of spacing.
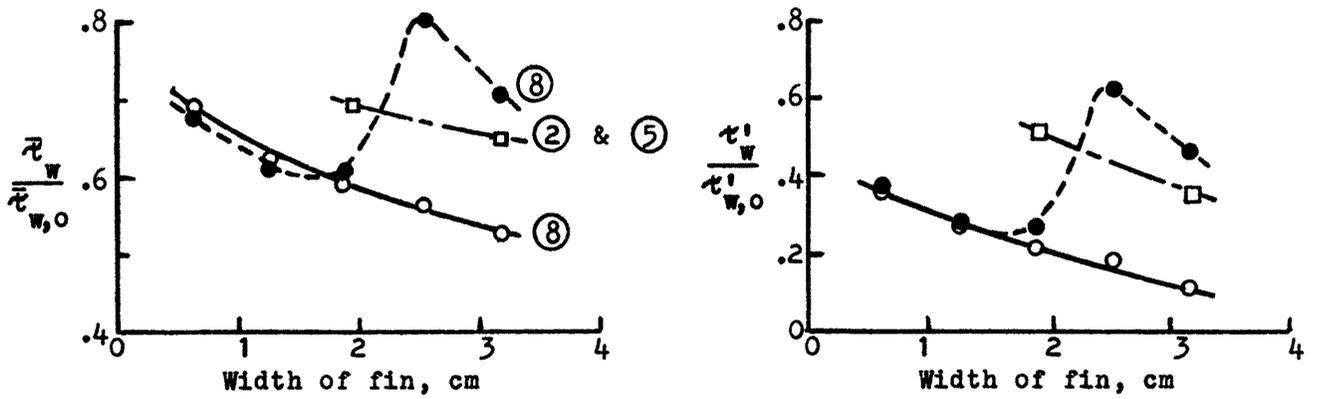
b) Effect of width.
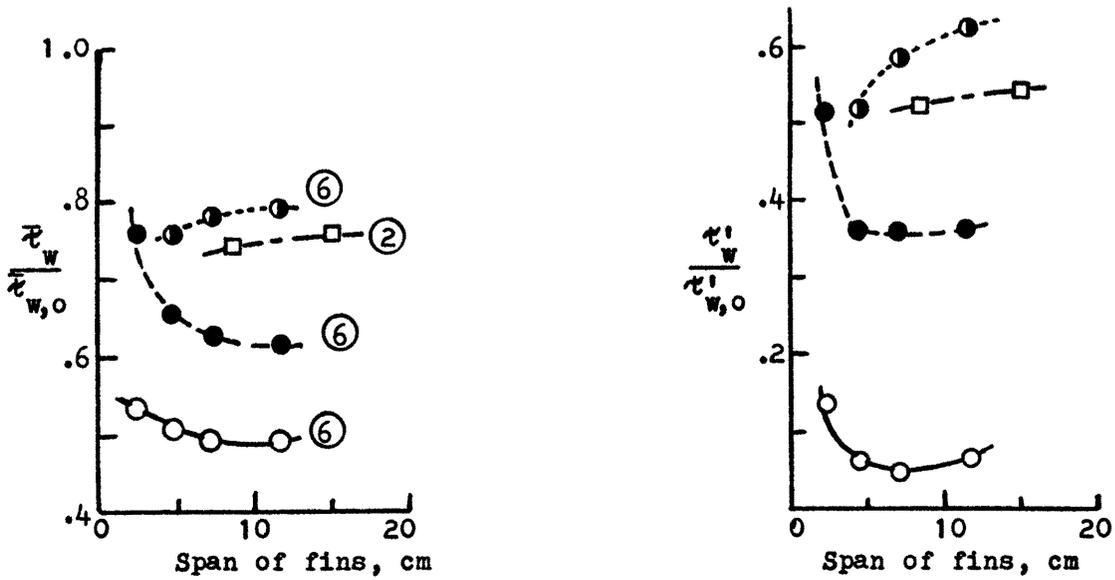
c) Effect of span.

Figure 8.- Effects of fin geometry on the mean and fluctuating surface shear.
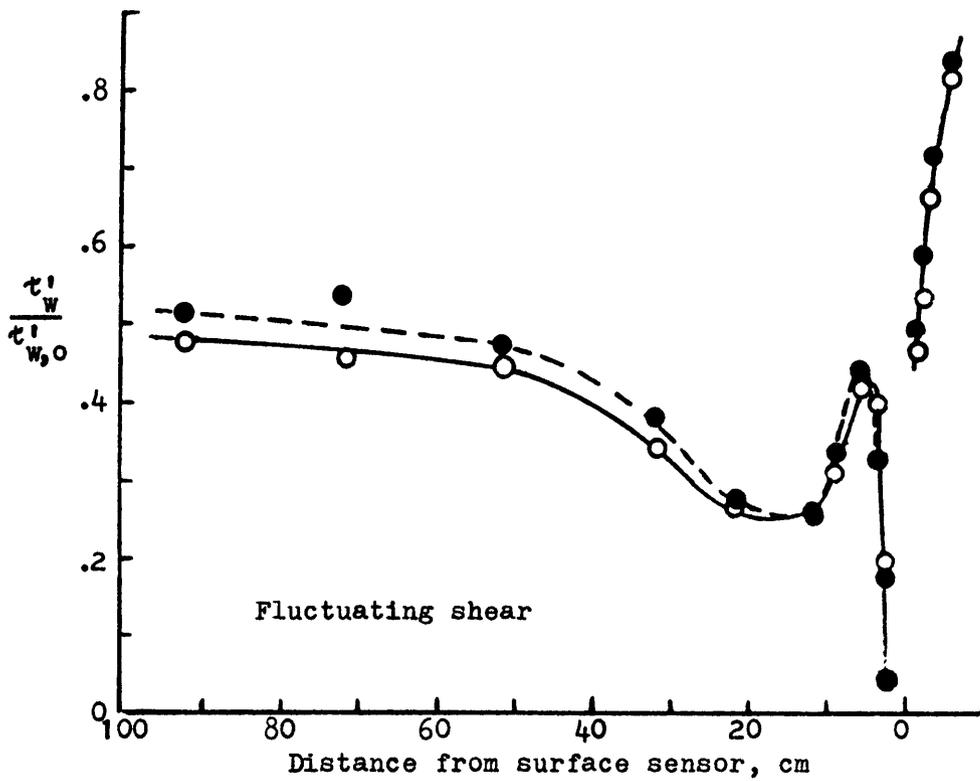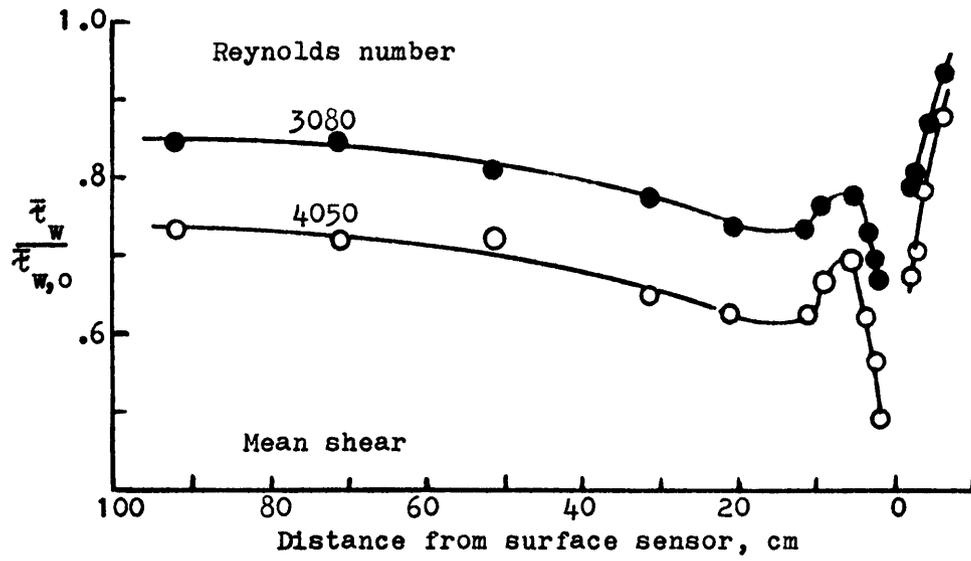
Figure 9.- Reynolds number variation for fin set number ①.
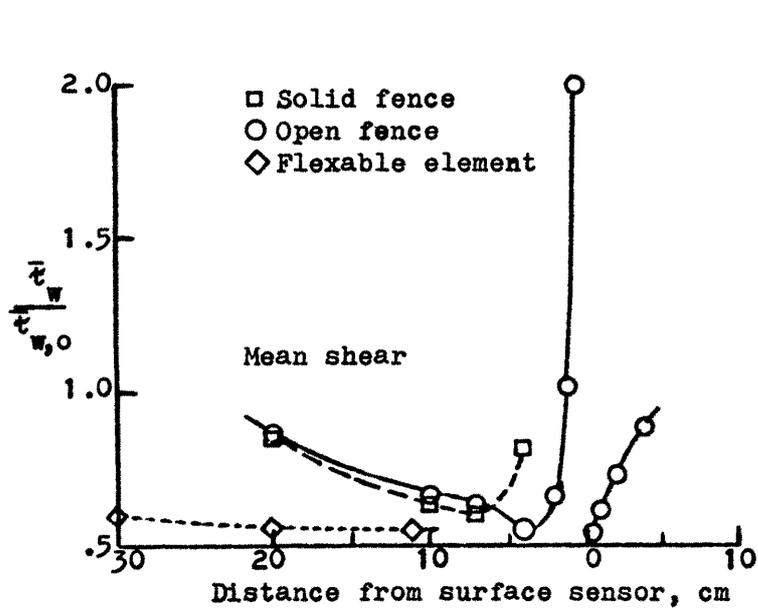
a) Fences and flexable element.
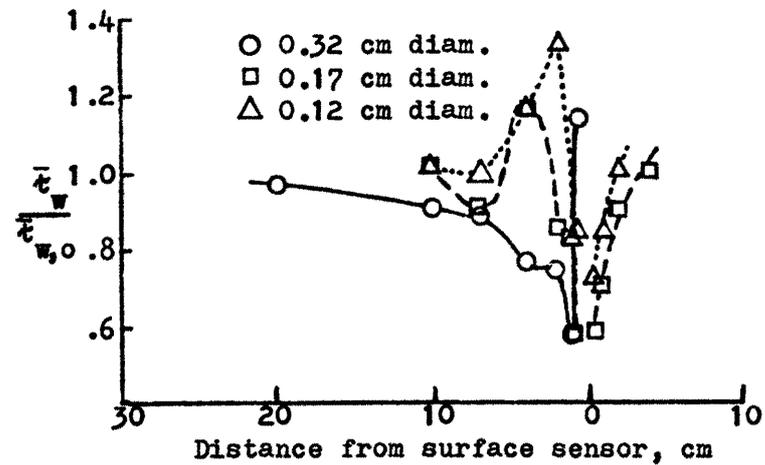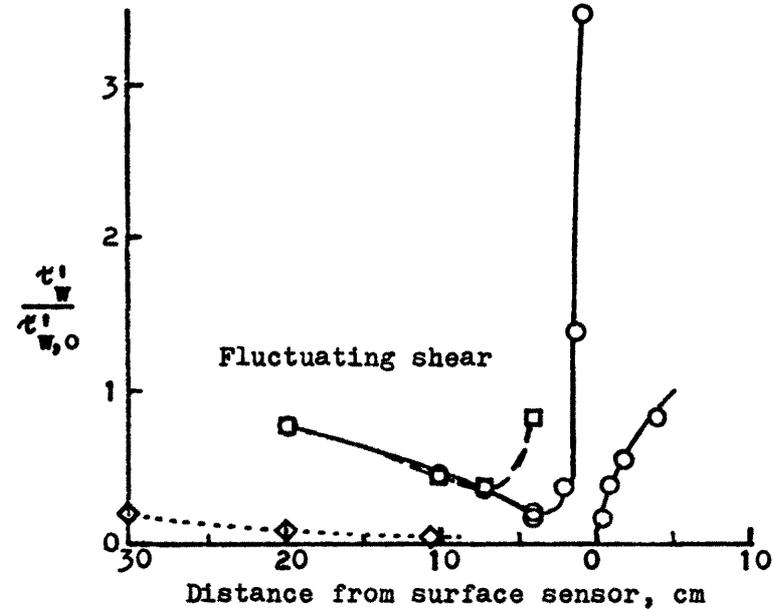
b) Rods on the surface.
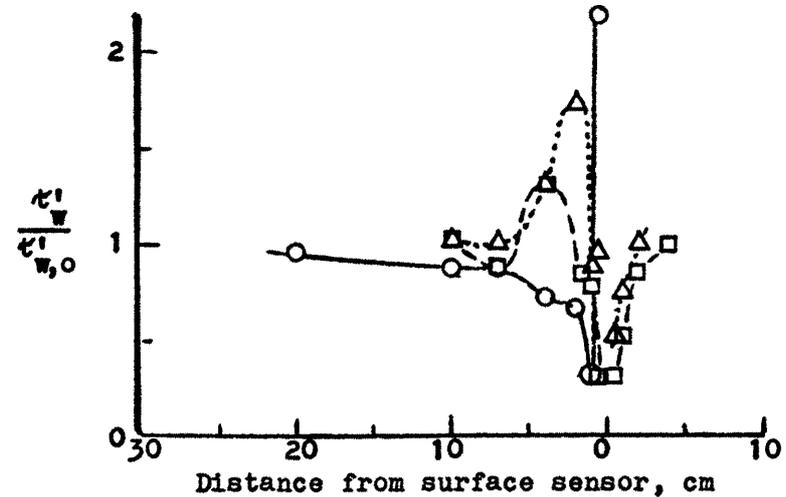
Figure 10.-Effect of different flow modification devices on the mean and fluctuating surface shear.
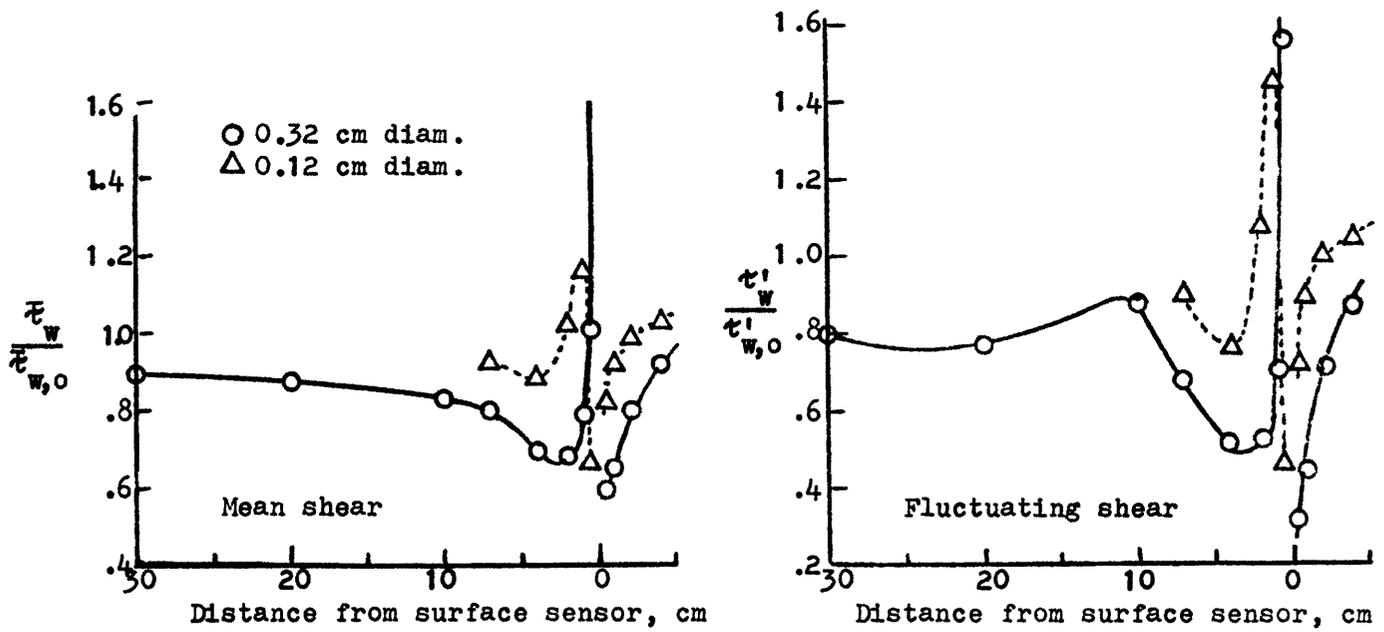
c) Rods above the surface.
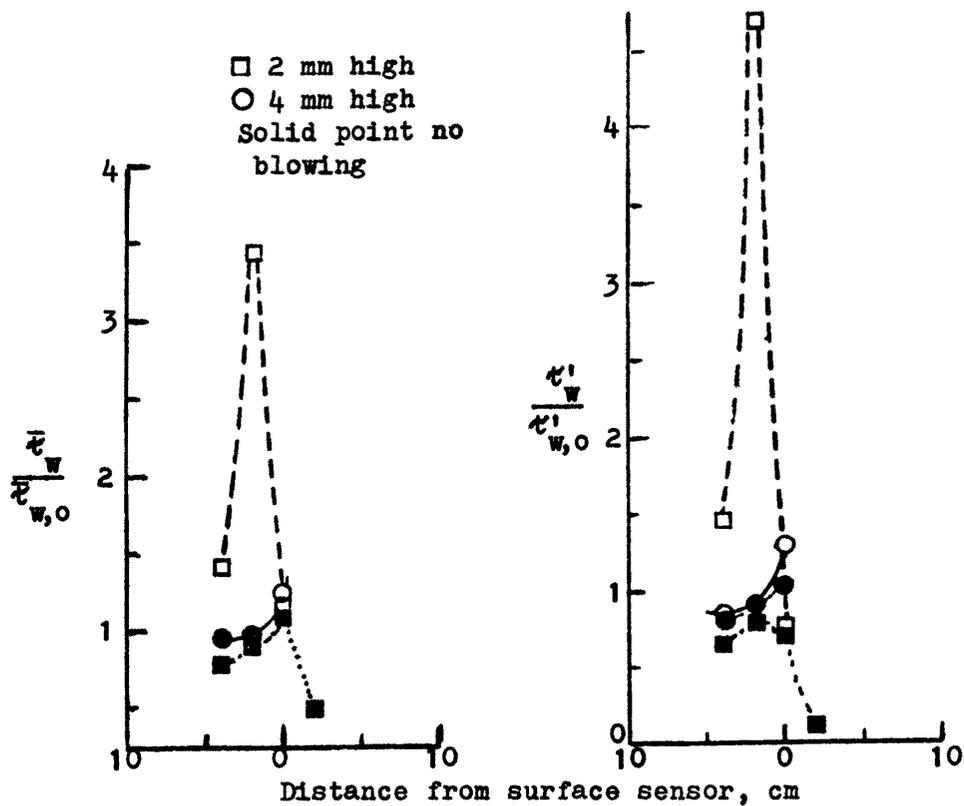
d) Blowing jet.

Figure 10.-(continued) Effect of different flow modification devices on the mean and fluctuating surface shear.
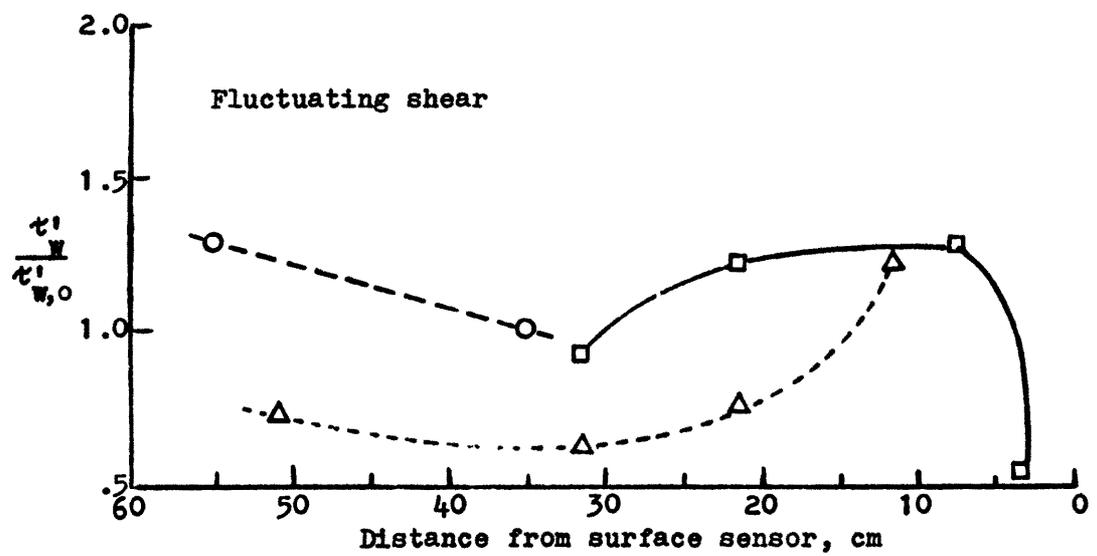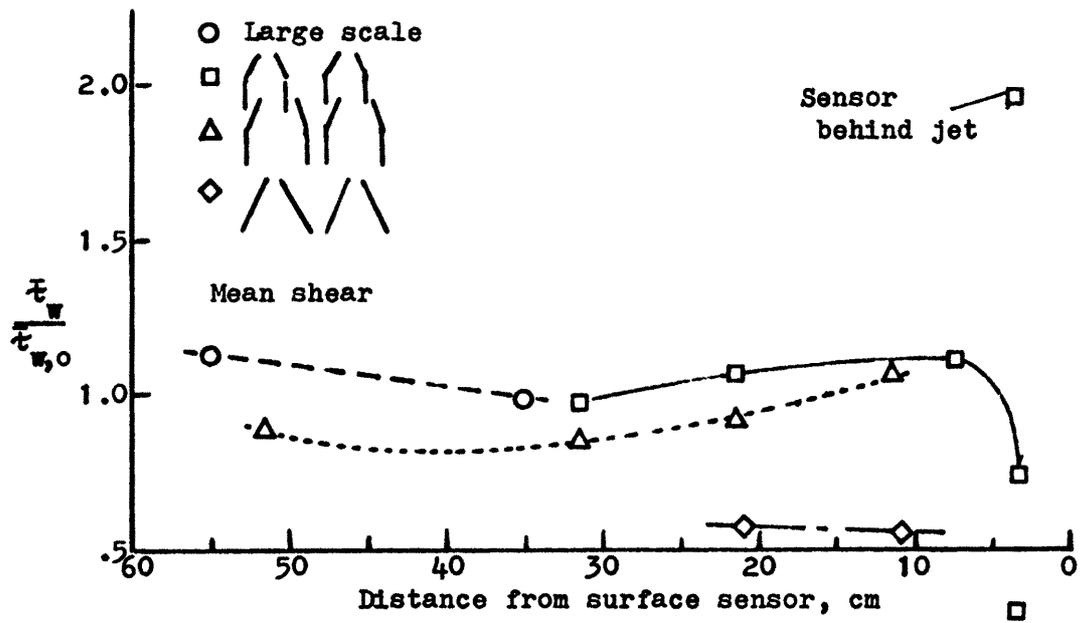
e) Vortex generators.

Figure 10.-(Concluded) Effect of different flow modification devices on the mean and fluctuating surface shear.
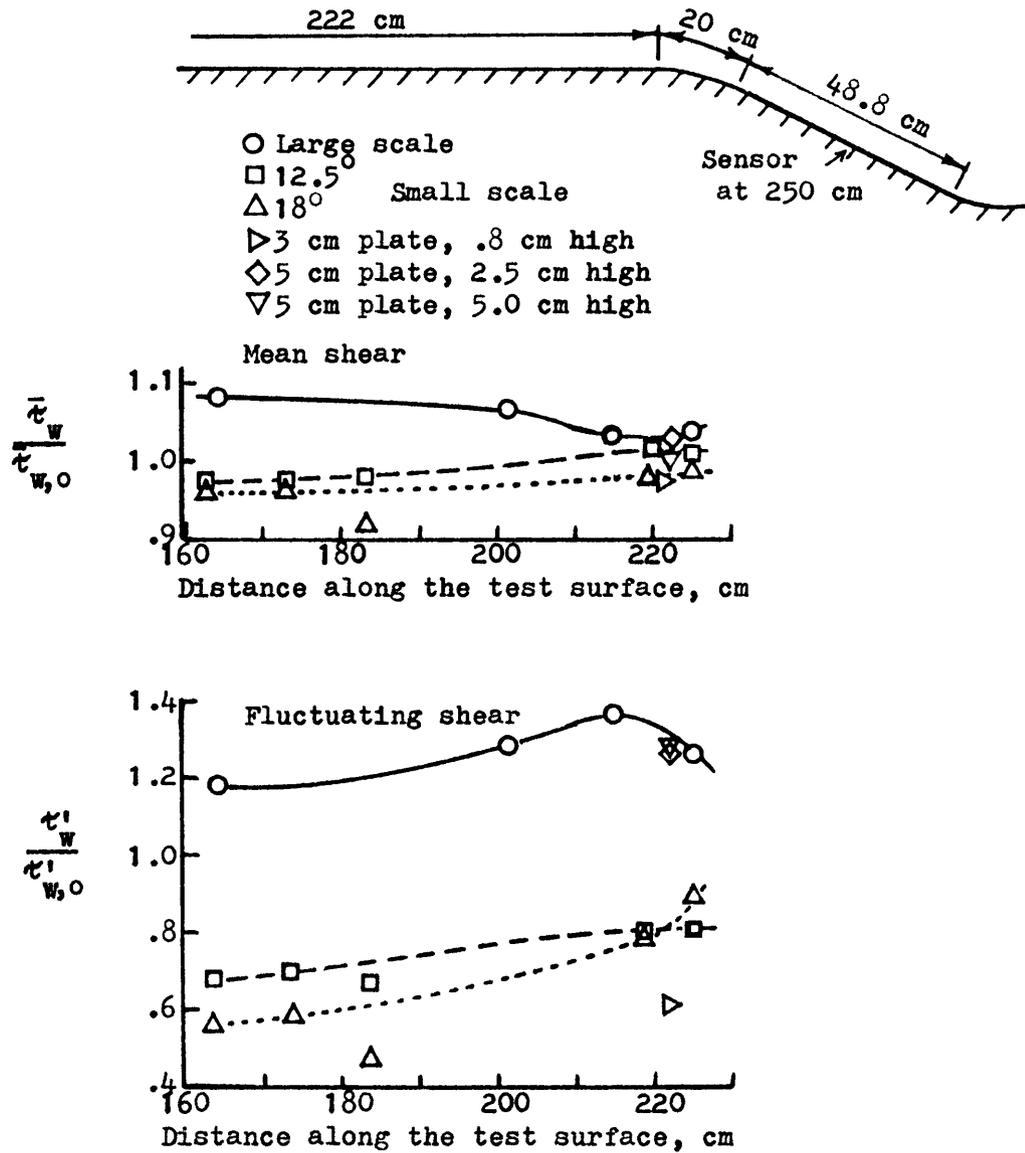
Figure 11.- Effect of vortex generators and deflection
plates on the surface shear in adverse
pressure gradients.

APPENDIX A

EVALUATION OF THE FLOW IN THE ADVERSE PRESSURE REGION

The wind tunnel test surface was constructed to produce a region of zero pressure gradient flow and then an expansion region of adverse pressure gradient flow sufficient to cause boundary layer separation. The actual set up of the test surface was shown in figure 1. Figure A-1 shows the analog evaluation of the potential flow coordinates for the model as it was set up in the tunnel. Although the potential flow analysis suggested a mild effect of the pressure gradient, the actual measurements indicate a more severe variation in the pressure. Figure 2 shows the measured static pressure along the model for three freestream approach velocities.

The flow was found to accelerate in the region of the initial model curvature and then has a very sharp increase in pressure once the curvature was reached. The sharp change in pressure at the start of the curvature was not desired. However, since the work was done concurrently with the upstream, flat plate measurements, Chien and Sandborn (1981), no attempt was made to re-adjust the model for fear of disturbing the upstream conditions.

The static pressure and mean velocity fields in the region from s = 247 cm to 276cm, where visual observations indicated separation was occurring, were determined from a pitot-and a disk type static-probe. Figures A-2 and A-3 show the measured static pressure and velocity variations at fixed heights above the surface. While flow visualization with dust indicated separation was occurring between s = 260 and 265cm, the surface static pressure still shows a definite increase. However, the static pressure above the surface at 3cm indicates very little change.

As a first approximation, the boundary layer velocity profiles along the potential coordinates have been evaluated. Figure A-4 shows the computed velocity profiles. The static pressure profiles are shown in figure A-5. The variation of the velocity profile,form factors,and momentum thickness Reynolds number are shown in figure A-6.

Whether the potential coordinate or a coordinate normal to the surface was used had little effect on the parameters for the s = 248 and 256cm stations. However, the parameters in the separation region are more sensitive to which coordinate system is used. Figure A-7 shows the boundary layer parameters compared with Sandborn-Kline (1961) separation correlations. The profiles at s = 266cm are close to the "intermittent" separation case. The velocity profiles at s = 273cm for u = 11.00 and 8.55m/sec. fall close to the zero-surface-shear-stress separation case. The estimate of the separation region from flow visualization is consistent with the intermittent separation correlations of Sandborn and Kline. The recently proposed separation criteron in terms of H and R_e, Sandborn (1979), is compared, figure A-8, with the present data. The values of H and R_e plotted on figure A-8 correspond to the points where the curves of figure A-7 cross the Sandborn-Kline correlation curve. While the agreement of the present data with the separation criterion shown on fig A-8 are reasonable, further considerations of the proper coordinates for defining the boundary layer profiles are indicated. The separation criteron of Sandborn (1979), is unfortunately based on the two data points shown. These two data points are subject to uncertainties of the same order as the present data.
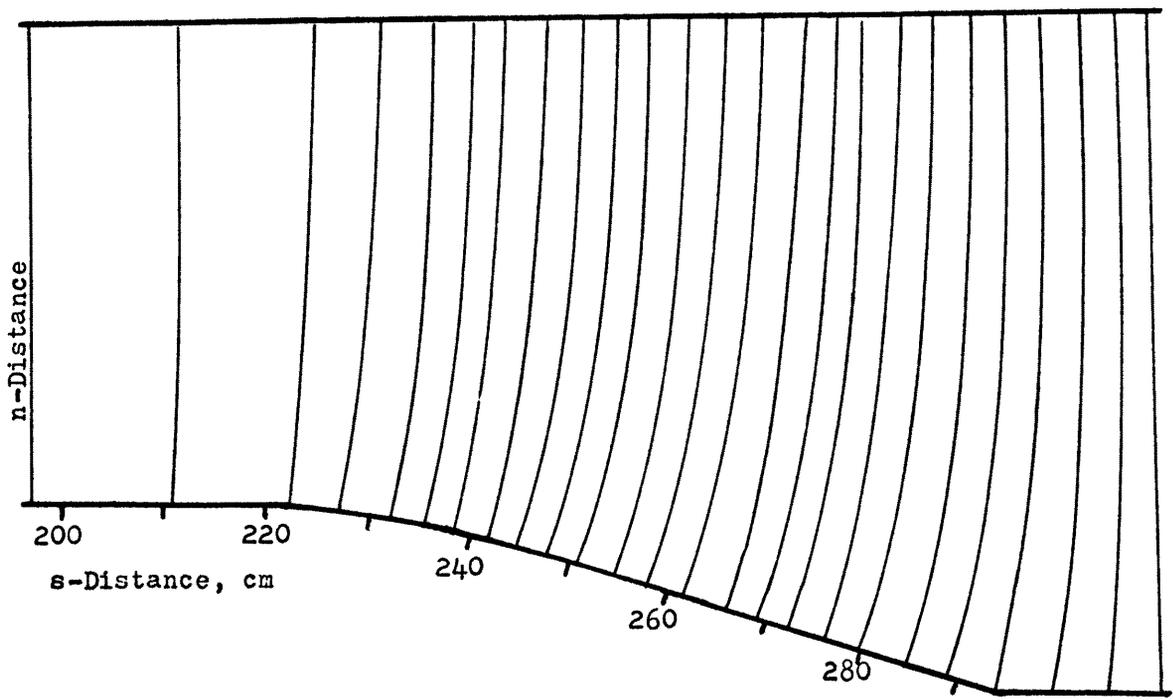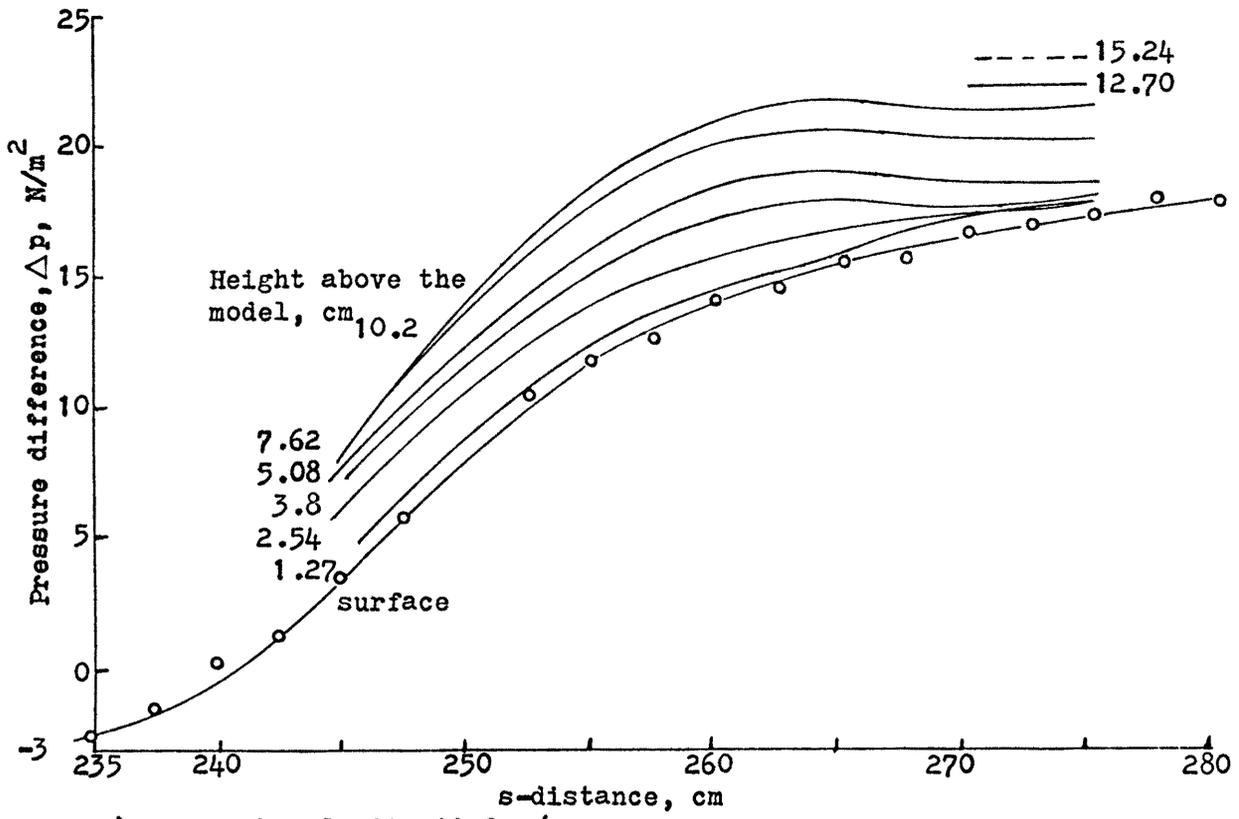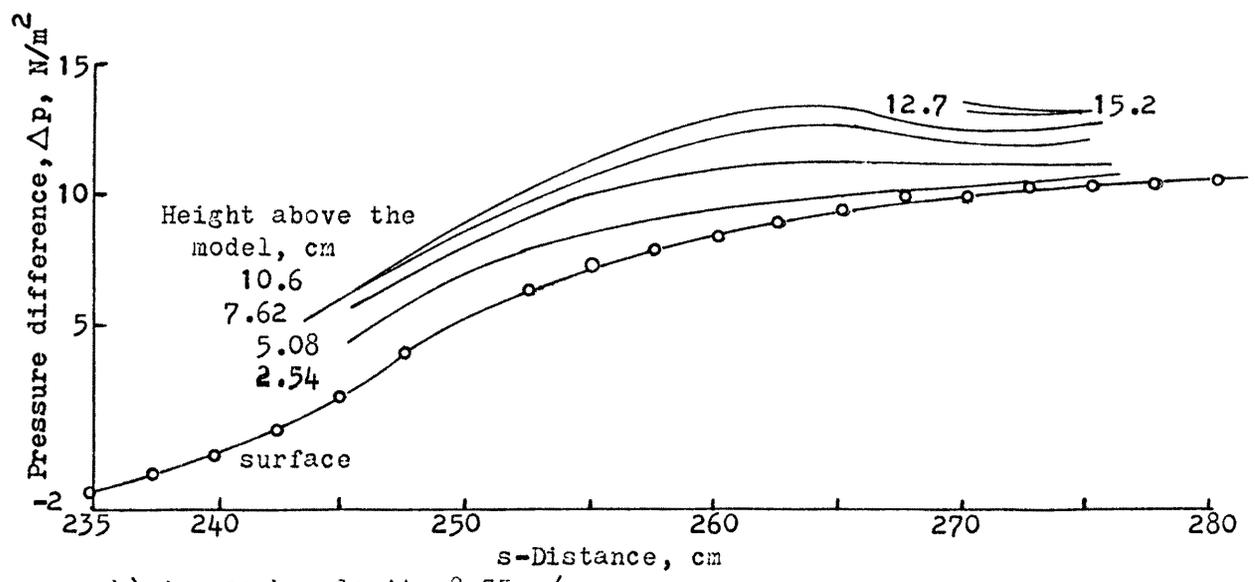
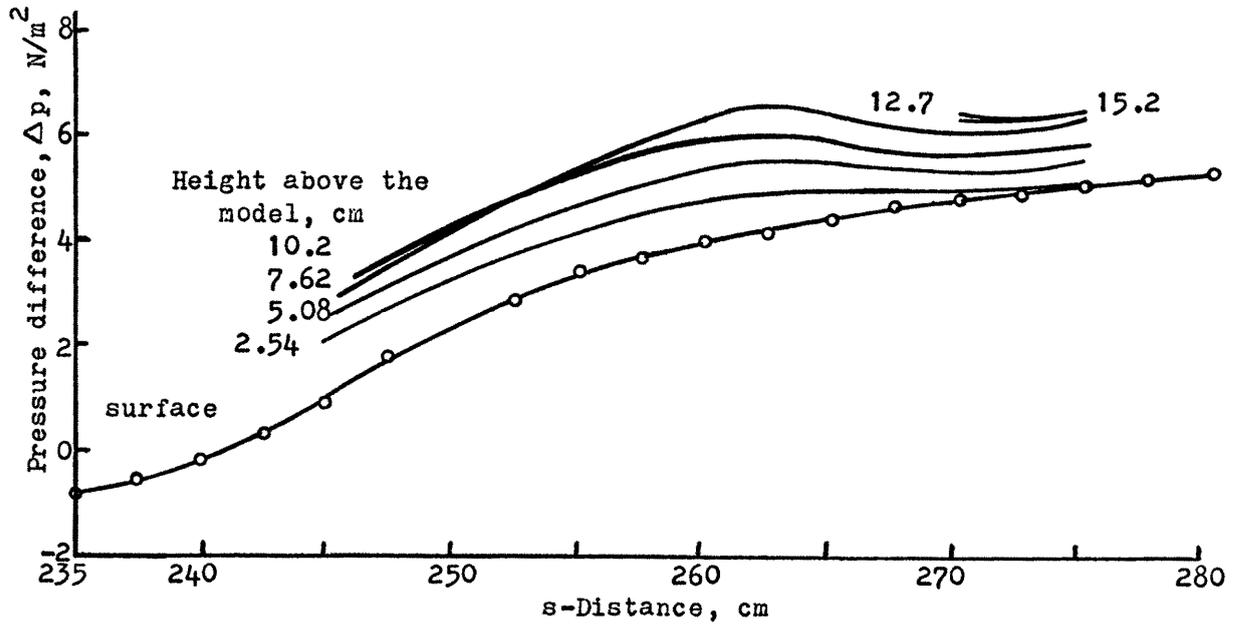Figure A-1. Wind Tunnel Contour With Equal Potential Lines.
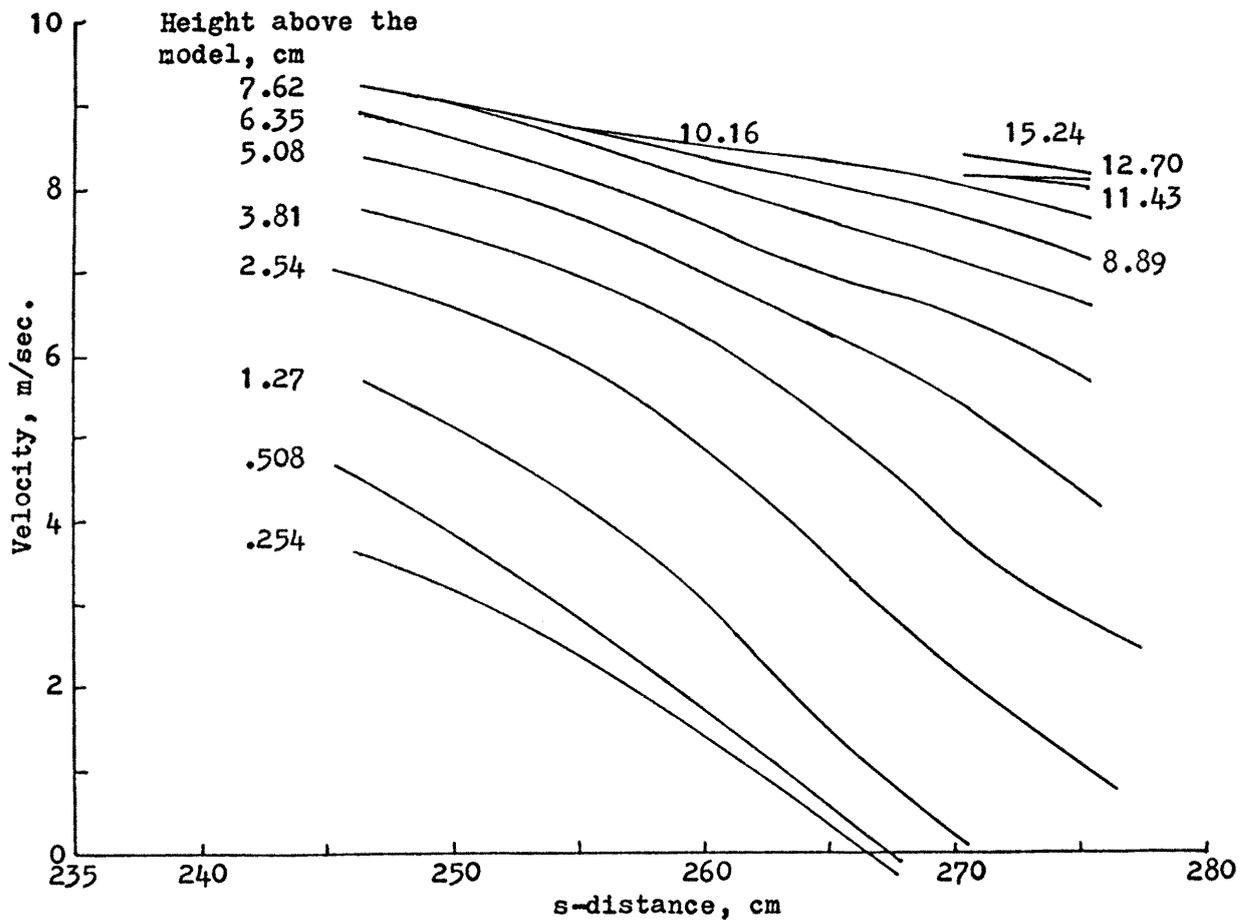
a) Approach velocity 11.0 m/sec.

b) Approach velocity 3.55 m/sec.

Figure A-2. Static pressure variation above the model surface.

c) Approach velocity 6.30 m/sec.

Figure A-2. (concluded) Static pressure variation above the model surface.

a) Approach velocity 11.0 m/sec.

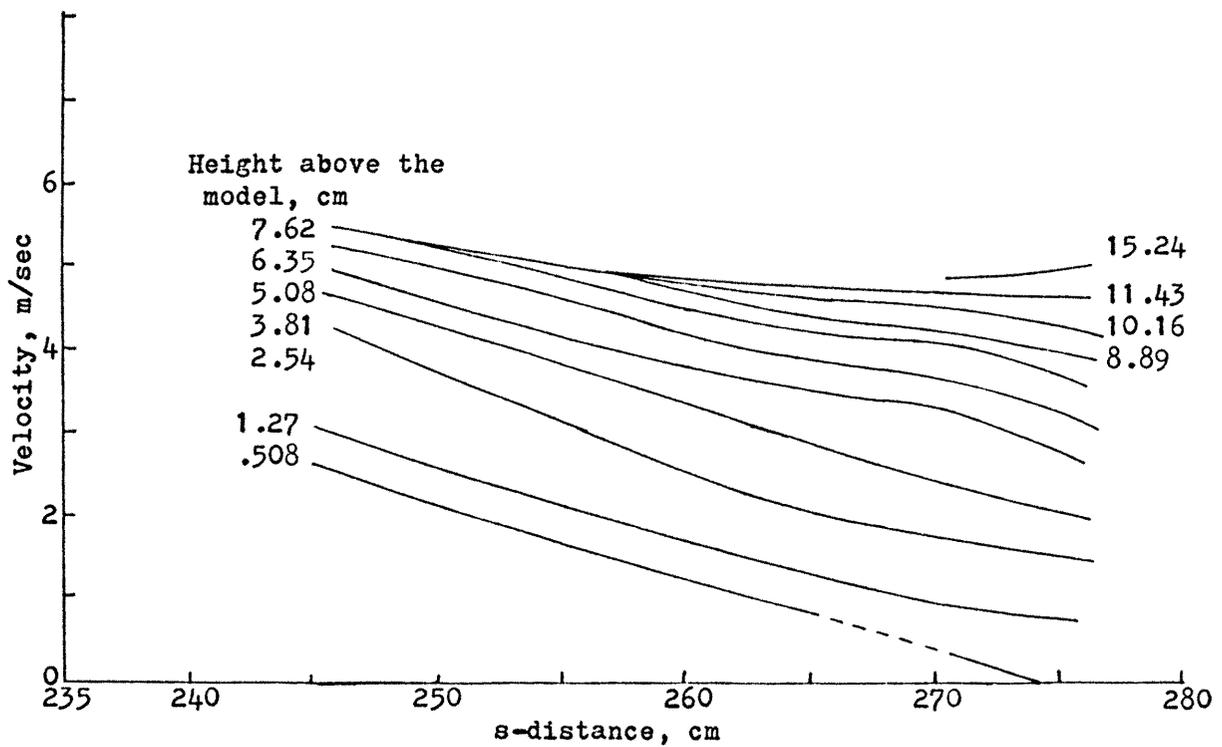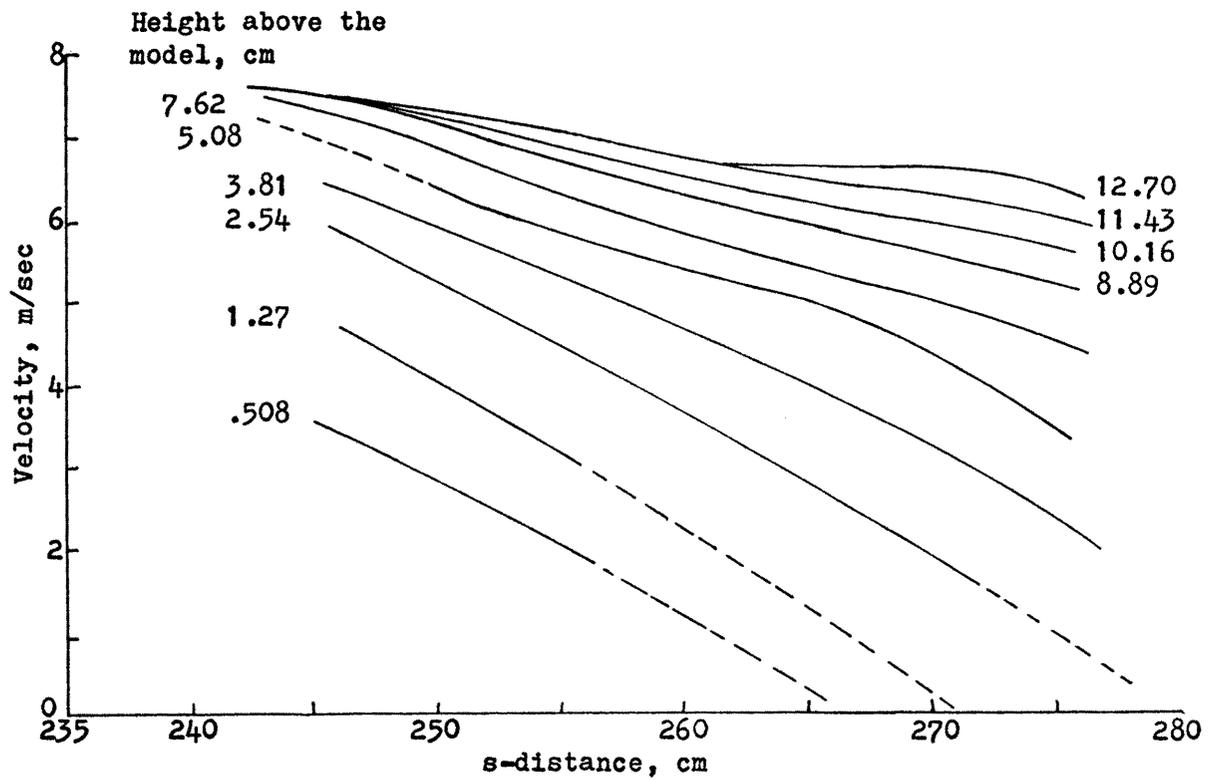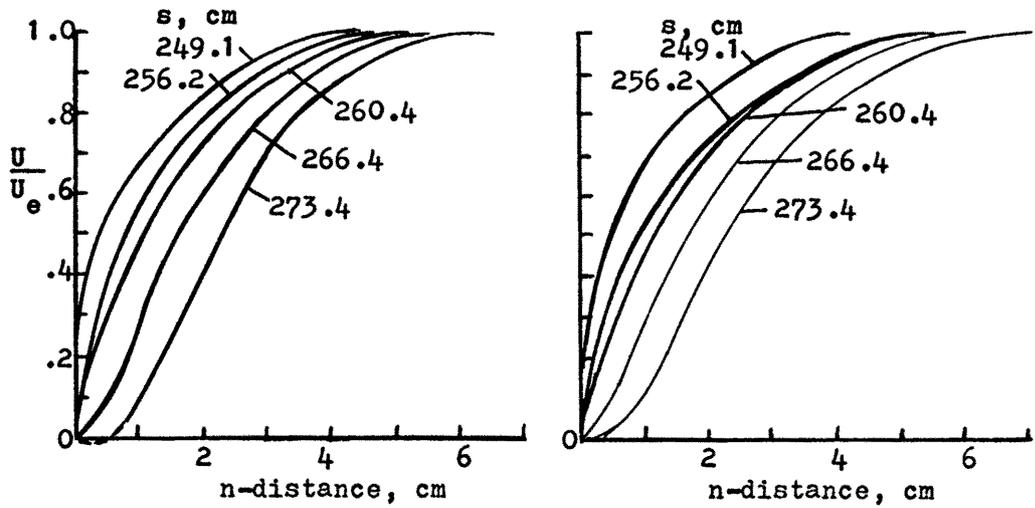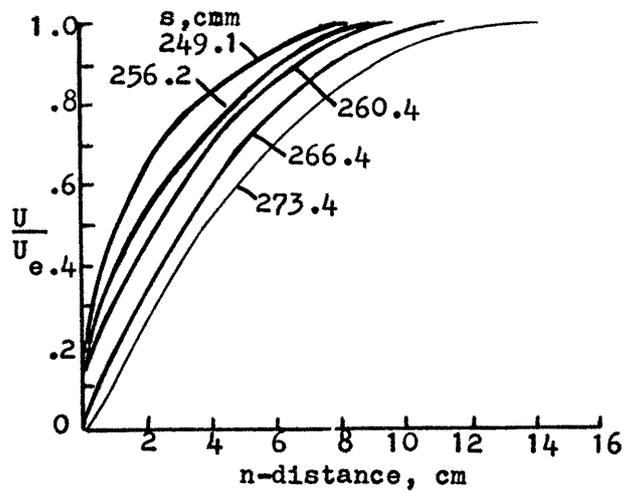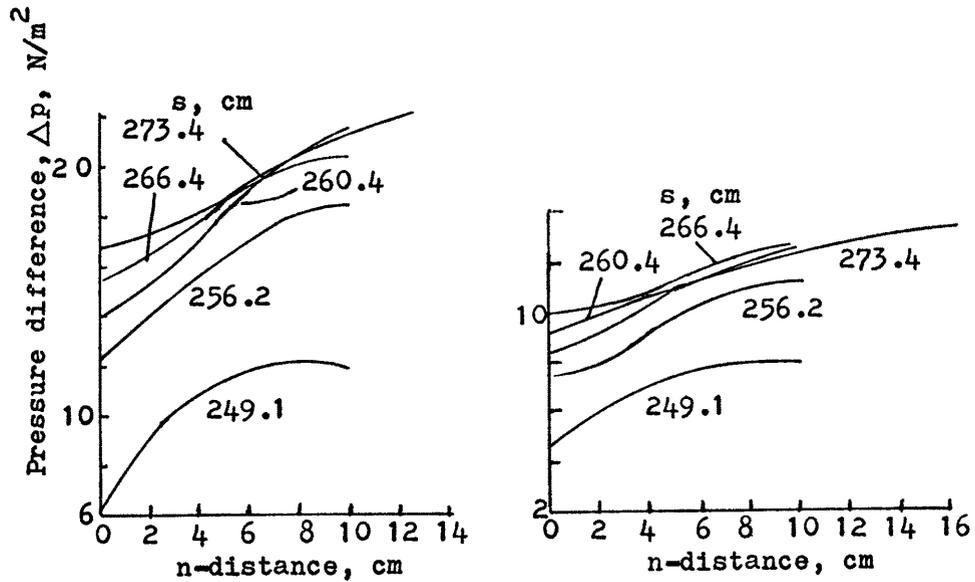Figure A-3. Mean velocity variation at fixed heights above the surface.

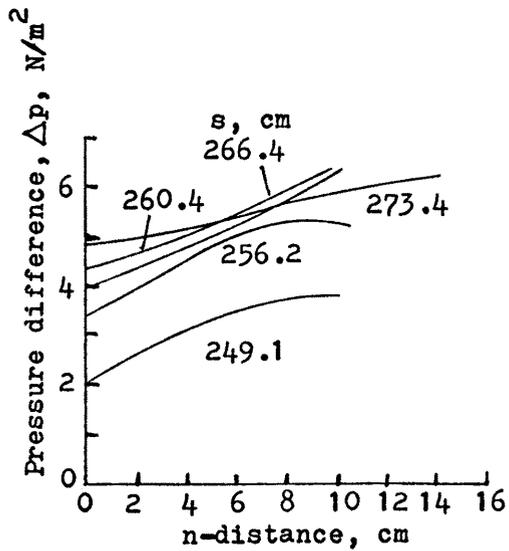b) Approach velocity 8.55 m/sec.

c) Approach velocity 6.30 m/sec.

Figure A-3. (concluded) Mean velocity variation at fixed heights above the surface

a) Approach velocity 11.0 m/s.　b) Approach velocity 8.55 m/s.

c) Approach velocity 6.30 m/s.
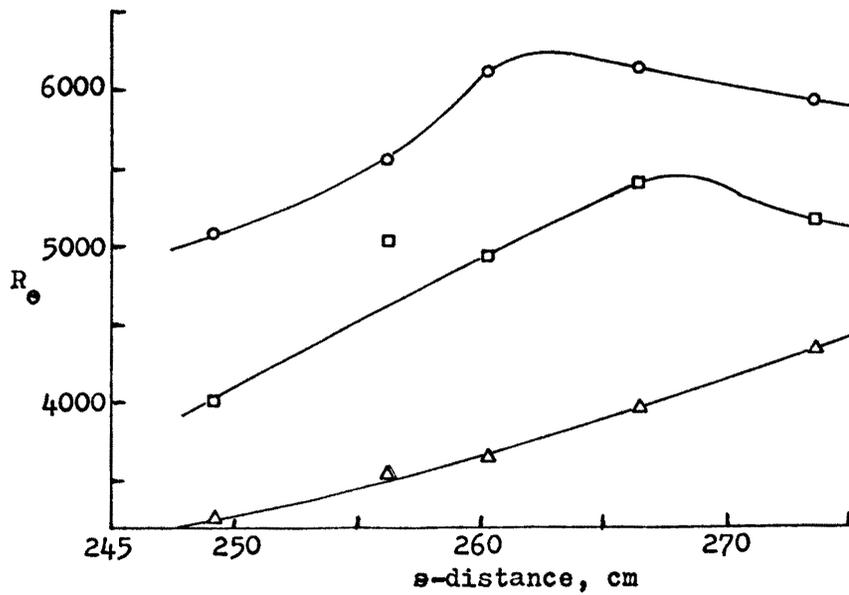
Figure A-4. Velocity distributions along the potential flow coordinates.

Figure A-5. Static pressure profiles along the potential
flow coordinate.
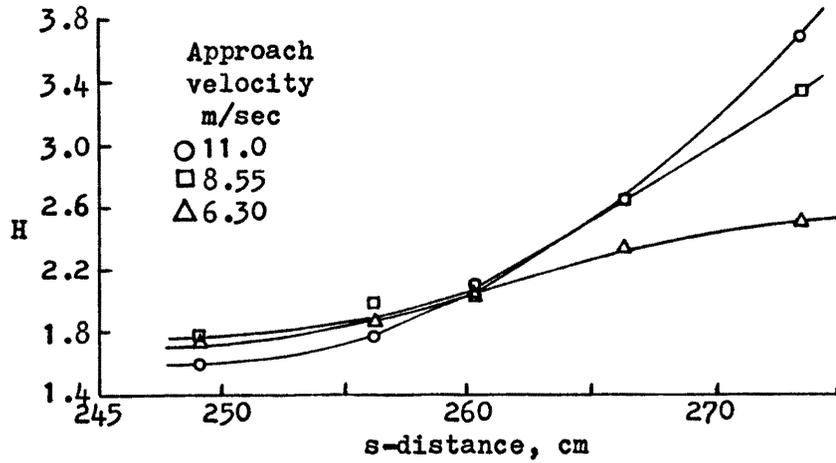
a) Form factor.

b) Momentum thickness Reynolds number.
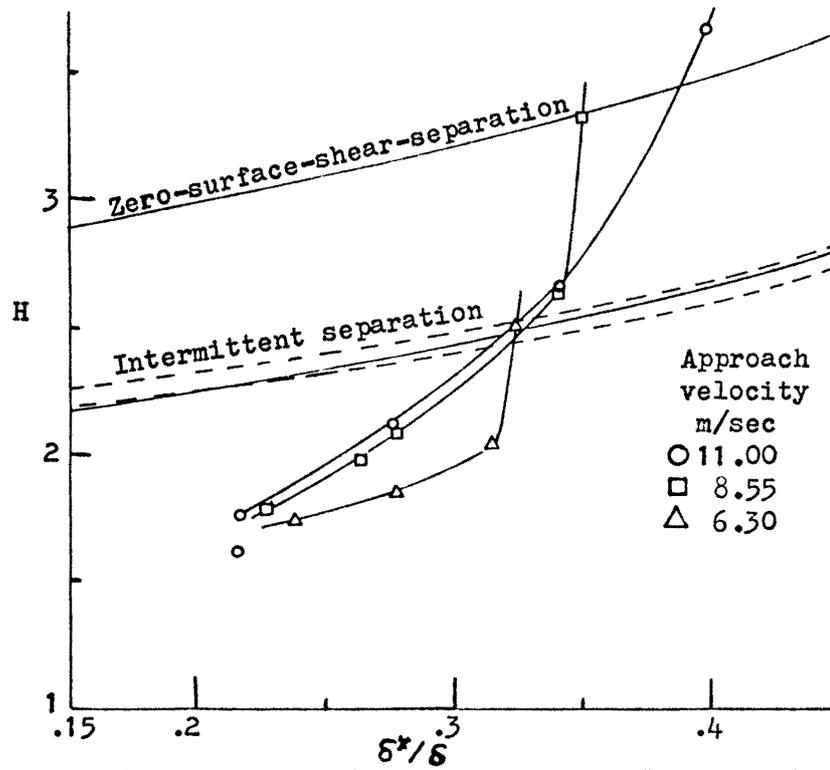
Figure A-6. Boundary layer parameters.

Figure A-7. Comparison of the velocity profile parameters with the Sandborn-Kline separation correlations.
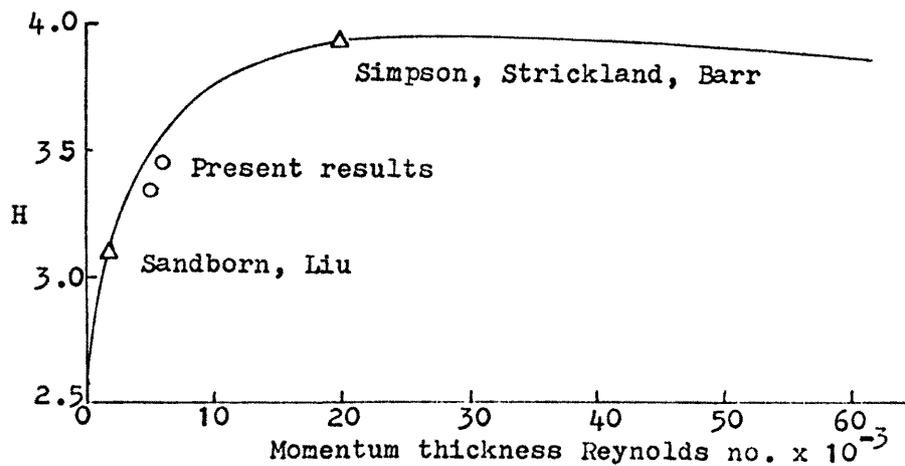

Figure A-8. Comparison of the zero-surface-shear-stress separation criterion of Sandborn (1979) with the measurements.