EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF ACCELERATION ON HEAT TRANSFER IN THE TURBULENT BOUNDARY LAYER

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Abstract

Rocket propulsion system components such as turbines/pumps and nozzles often have aerodynamically-rough surfaces or surfaces which become rough during operation. Also, these surfaces are often in regions of accelerating flow. The interaction between surface roughness and acceleration is complicated and not predicted by a simple superposition of flat-plate rough-wall correlations and smooth-wall acceleration effects.

For the smooth wall, acceleration causes a decrease in the Stanton number when compared with equivalent unaccelerated flow. When the acceleration is strong enough, the turbulent boundary-layer heat transfer rates will approach those of a laminar flow and the boundary layer is said to have relaminarized. Under proper conditions, rough-wall accelerated flow can have the opposite behavior with increasing Stanton numbers and hence much larger heat transfer rates.

The objective of this research was to experimentally investigate the combined effects of freestream acceleration and surface roughness on heat transfer and fluid flow in the turbulent boundary layer. The experiments included a variety of flow conditions ranging from aerodynamically-smooth to transitionally-rough to fully-rough boundary layers with accelerations ranging from moderate to moderately strong. The test surfaces used were a smooth-wall test surface and two rough-wall test surfaces which were roughened with 1.27 mm diameter hemispheres spaced 2 and 4 base diameters apart in a staggered array. The experiments were conducted in the Turbulent Heat Transfer Test Facility in the mechanical engineering laboratories at Mississippi State University. The measurements consisted of Stanton number distributions, mean-temperature profiles, skin-friction distributions, mean-velocity profiles, turbulence-intensity profiles, and Reynolds-stress profiles.

The Stanton numbers for the rough-wall experiments increased with acceleration. For aerodynamically-smooth and transitionally-rough boundary layers, the effect of the roughness is not seen immediately at the beginning of the accelerated region as it is for fully-rough boundary layers; however, as the boundary layer thins under acceleration, the surface becomes relatively rougher resulting in a sharp increase in Stanton number.

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April 26, 1995

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BACKGROUND

- Acceleration effects on smooth-wall boundary layers--strong accelerations cause sharp decrease in the Stanton number

$$K = \frac{\nu}{U_e^2} \frac{dU_e}{dx}$$

$K > 3.0 \times 10^{-6}$ relaminarization

- Fully-rough boundary layers react to acceleration in the opposite way--Stanton number increases under acceleration.

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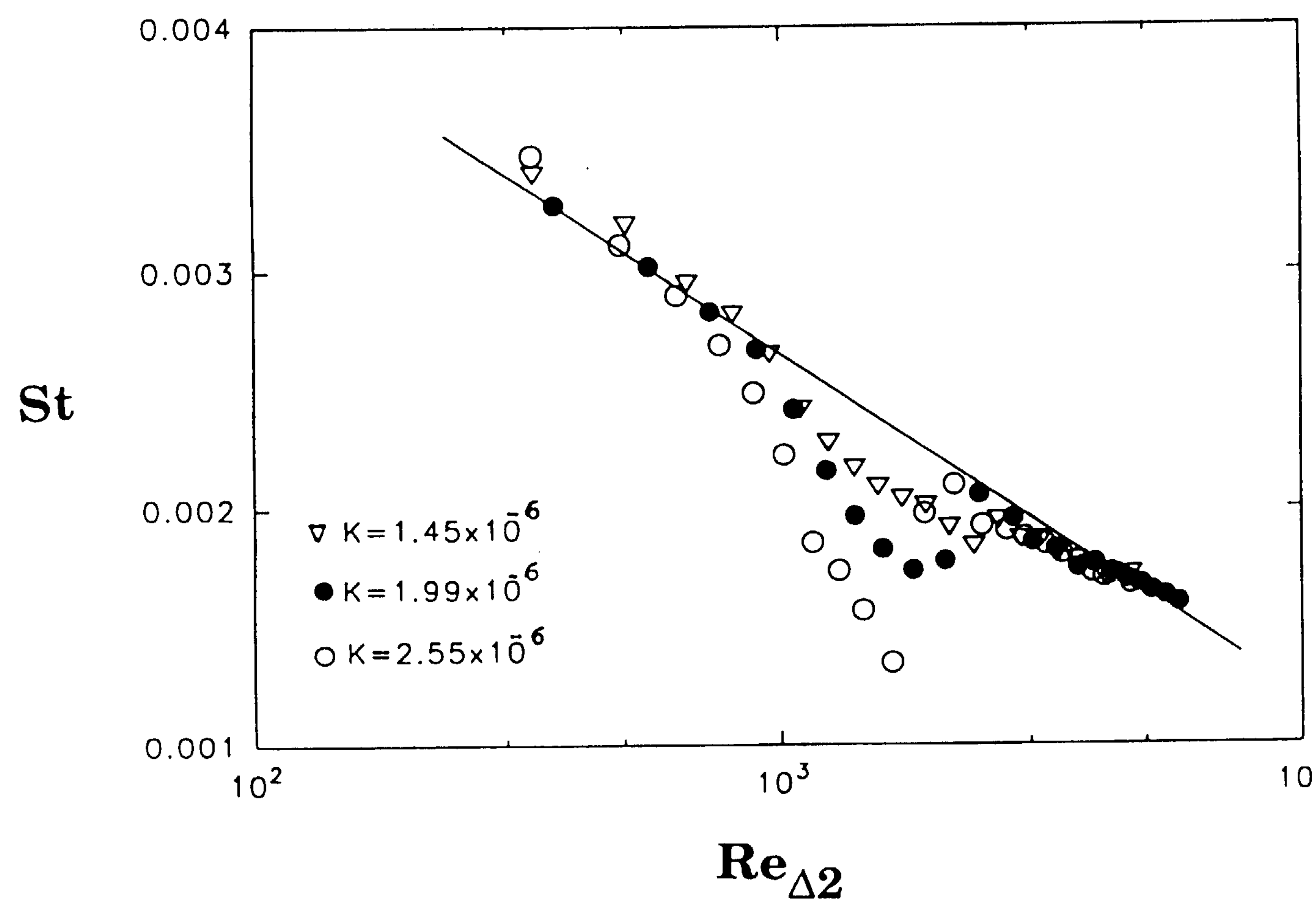

Effects of acceleration on smooth-wall turbulent Stanton numbers, from Kays and Moffat (1975)

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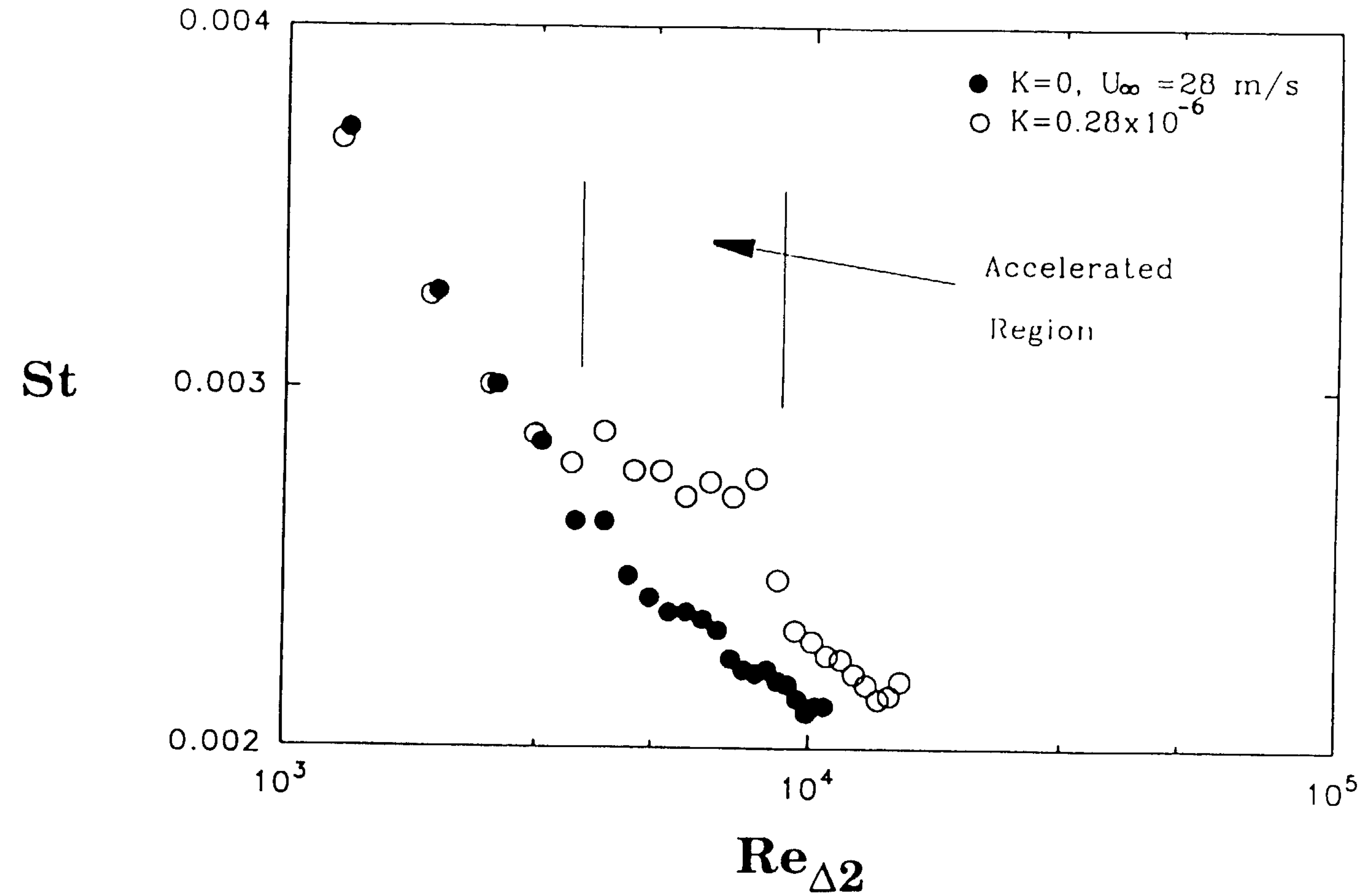

Effects of acceleration on full-rough turbulent Stanton numbers, from Coleman (1976)

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- In a smooth-wall boundary layer, acceleration stretches the eddies **reducing the trans-boundary-layer diffusion**, decreases the boundary-layer thickness, **increases the viscous sublayer thickness**, and ***reduces the Stanton number***.

- In a **fully-rough** boundary layer, acceleration stretches the eddies reducing the trans-boundary-layer diffusion, **decreases the boundary-layer thickness**, **increases the nondimensional size of the roughness elements**, and ***increases the Stanton number***.

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OBJECTIVES OF THIS WORK

- Experimentally investigate the effects of freestream acceleration on heat transfer in the turbulent rough-wall boundary layer.
- Investigate a variety of flow conditions ranging from aerodynamically-smooth to fully-rough boundary layers.

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EXPERIMENTS

- Closed-loop boundary-layer wind tunnel with 2.5-m long test section.
- Flexible top wall to adjust edge velocity.
- Rough-wall boundary-layer thickness of about 5 cm.
- Roughness made with 1.27-mm diameter hemispheres spaced 2 and 4 diameters apart.
- Stanton numbers determined form energy balance on individual plates.
- Velocity and turbulence profiles measured with hot-wire anemometry.

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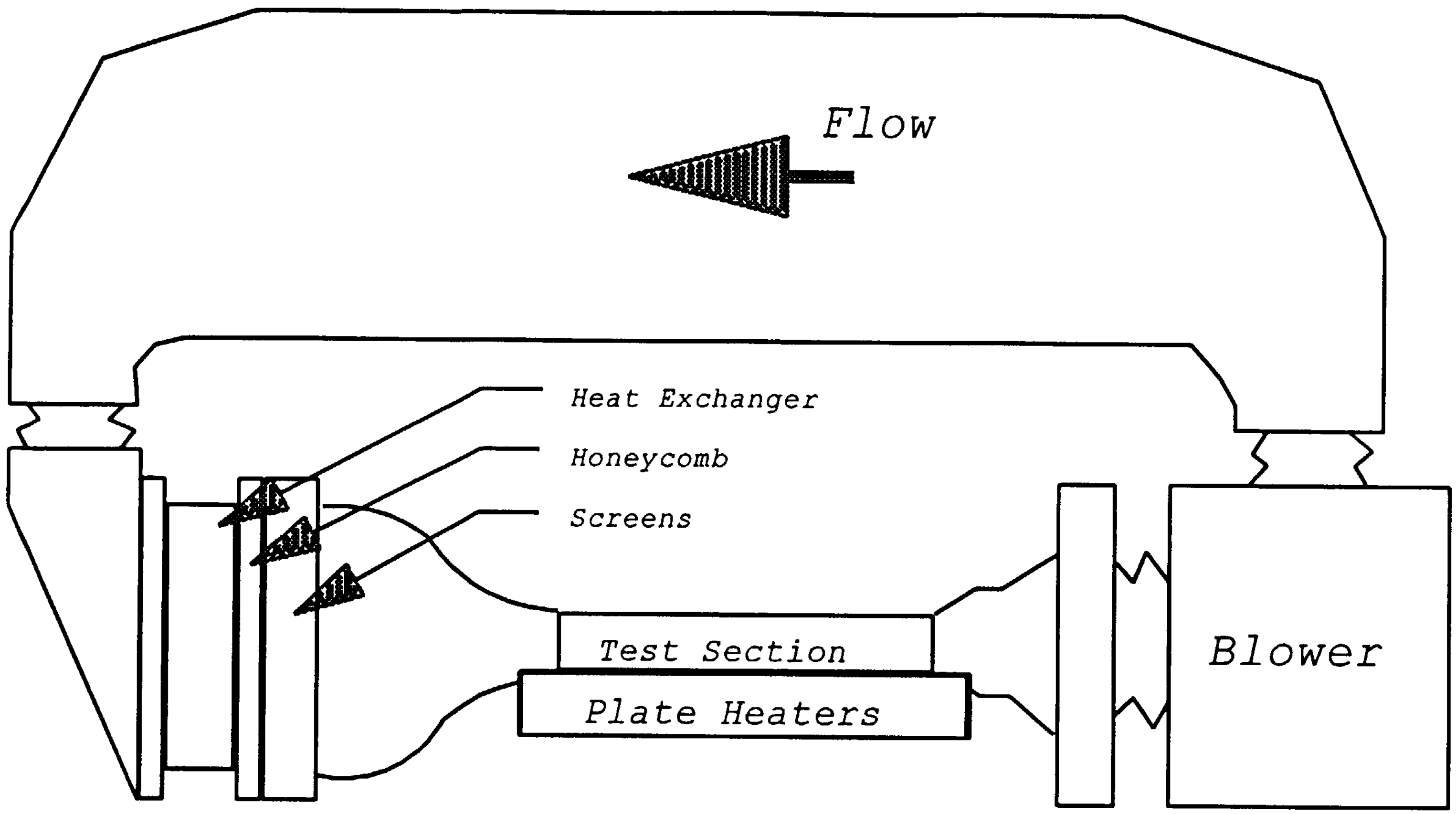

Turbulent heat transfer test facility

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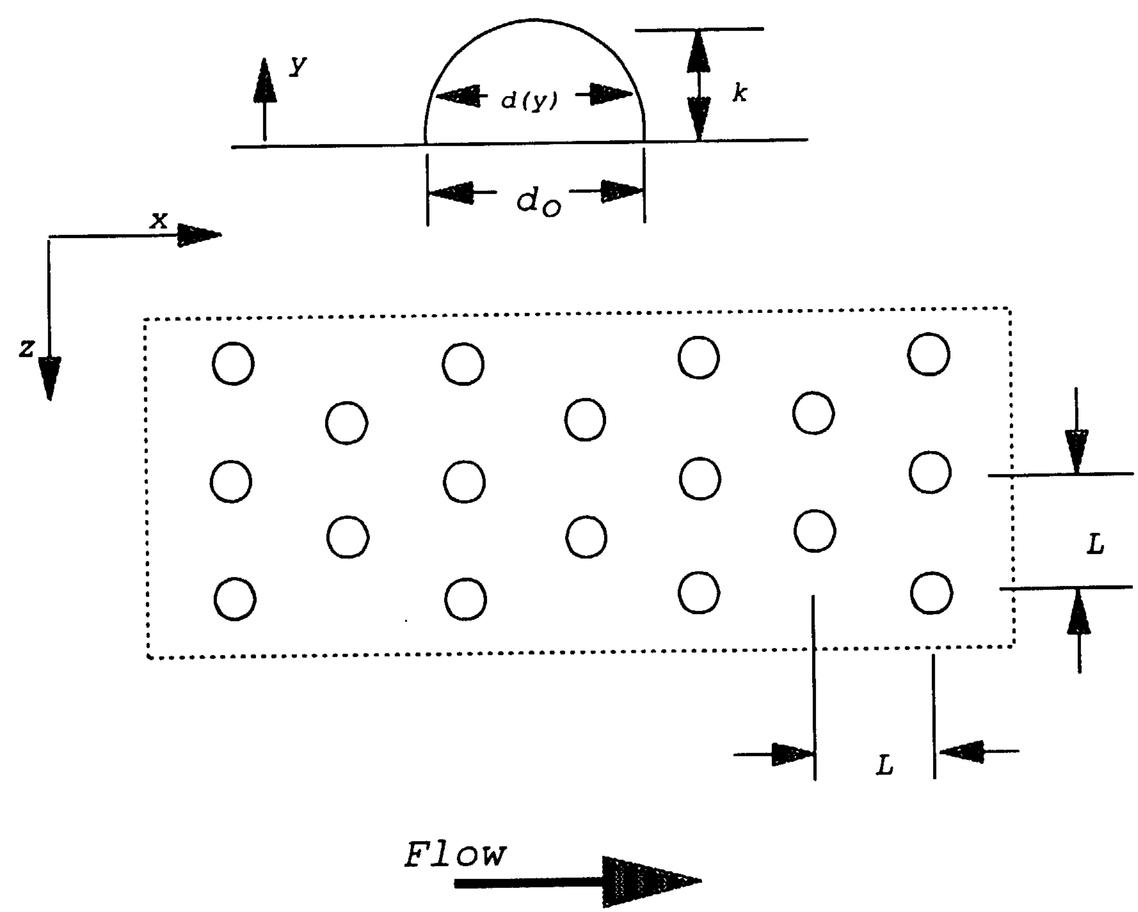

Surface roughness description

HEAT TRANSFER DATA

$K \times 10^6$	U_∞ m/s	$L/d_o = 2$	$L/d_o = 4$
0.3	28	fully rough	fully rough
0.6	12	fully rough	tran'ly rough
0.9	8	tran'ly rough	tran'ly rough
1.4	5	aero'ly smooth	aero'ly smooth

Roughness state based on the boundary layer conditions just upstream of the accelerated region.

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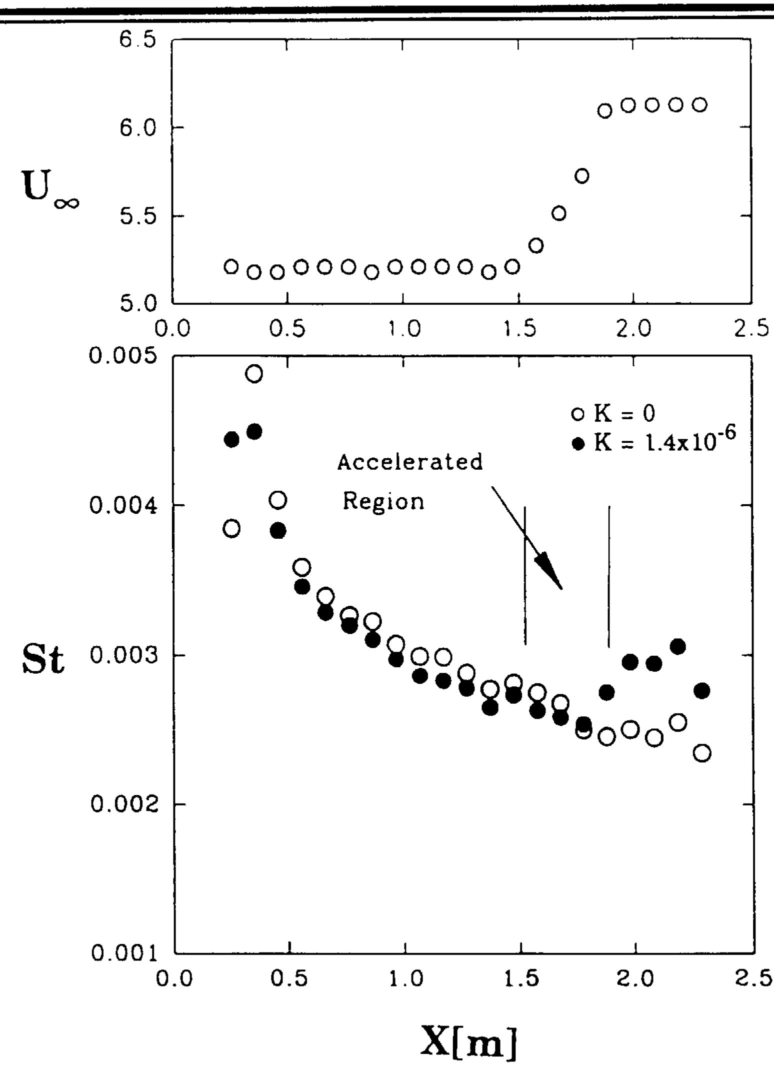

$K = 1.4 \times 10^{-6}$, $L/d_o = 2$, aerodynamically-smooth approaching flow

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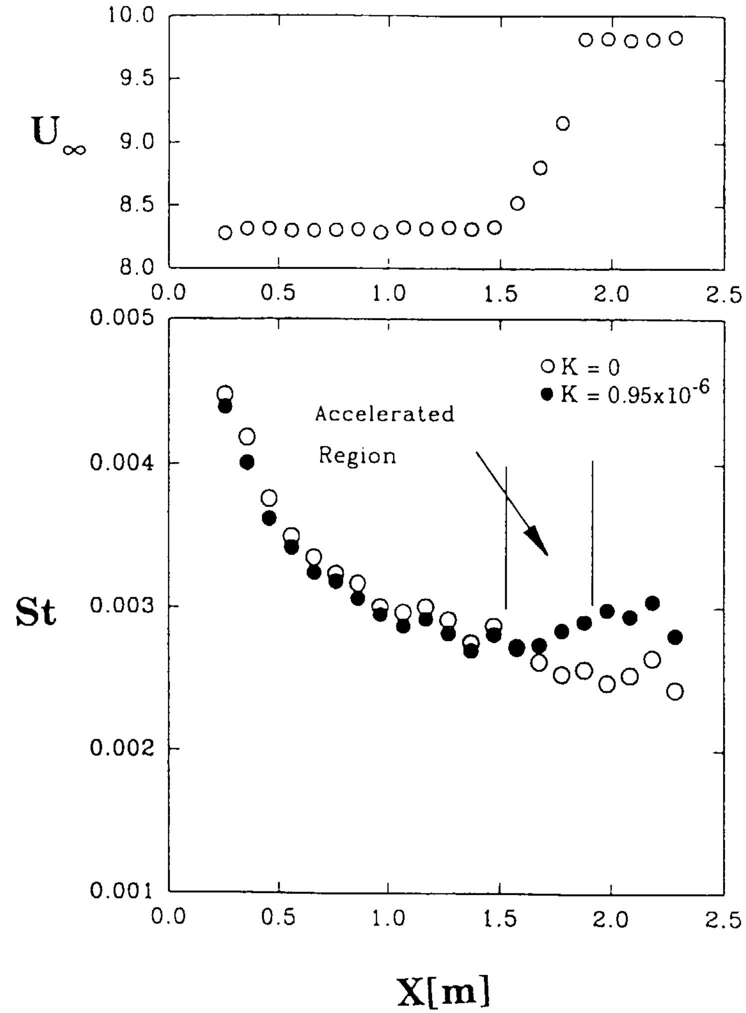

$K = 0.95 \times 10^{-6}$, $L/d_o = 2$, transitionally-rough approaching flow

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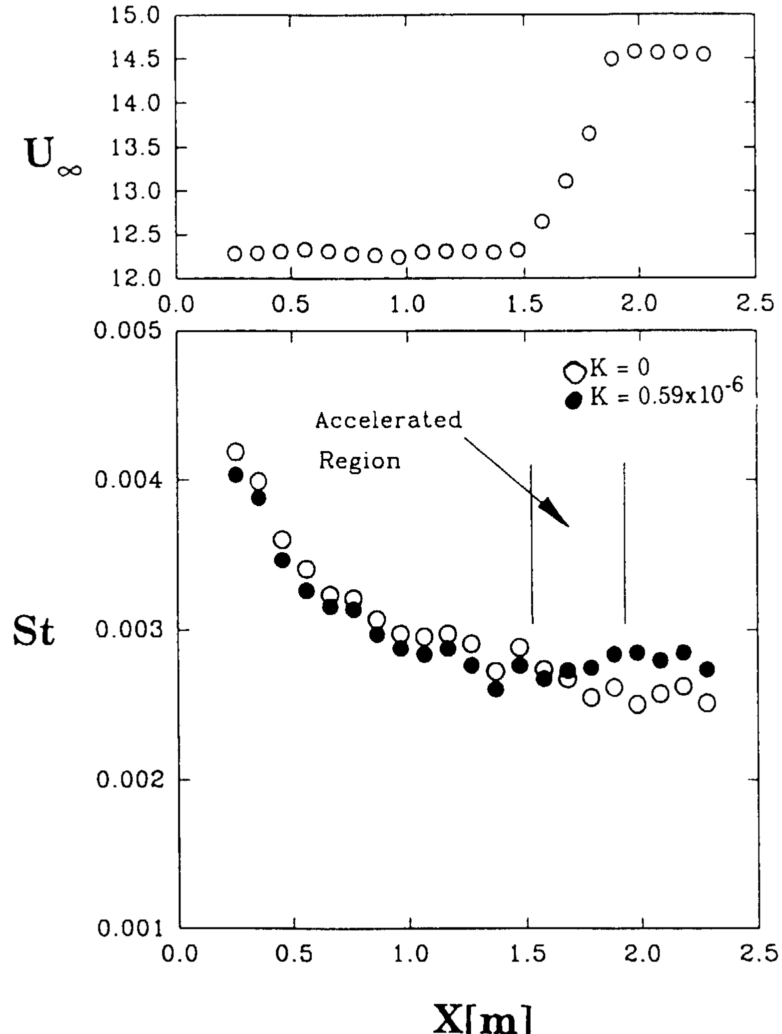

$K = 0.59 \times 10^{-6}$, $L/d_o = 2$, fully-rough approaching flow

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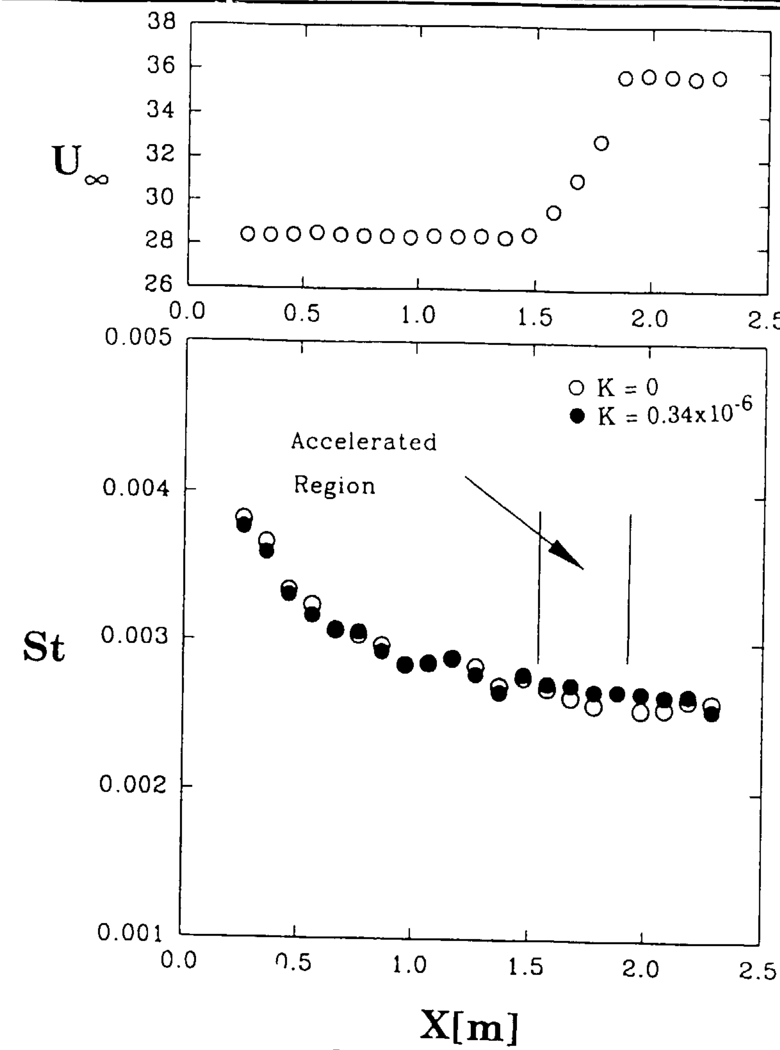

$K = 0.34 \times 10^{-6}$, $L/d_o = 2$, fully-rough approaching flow

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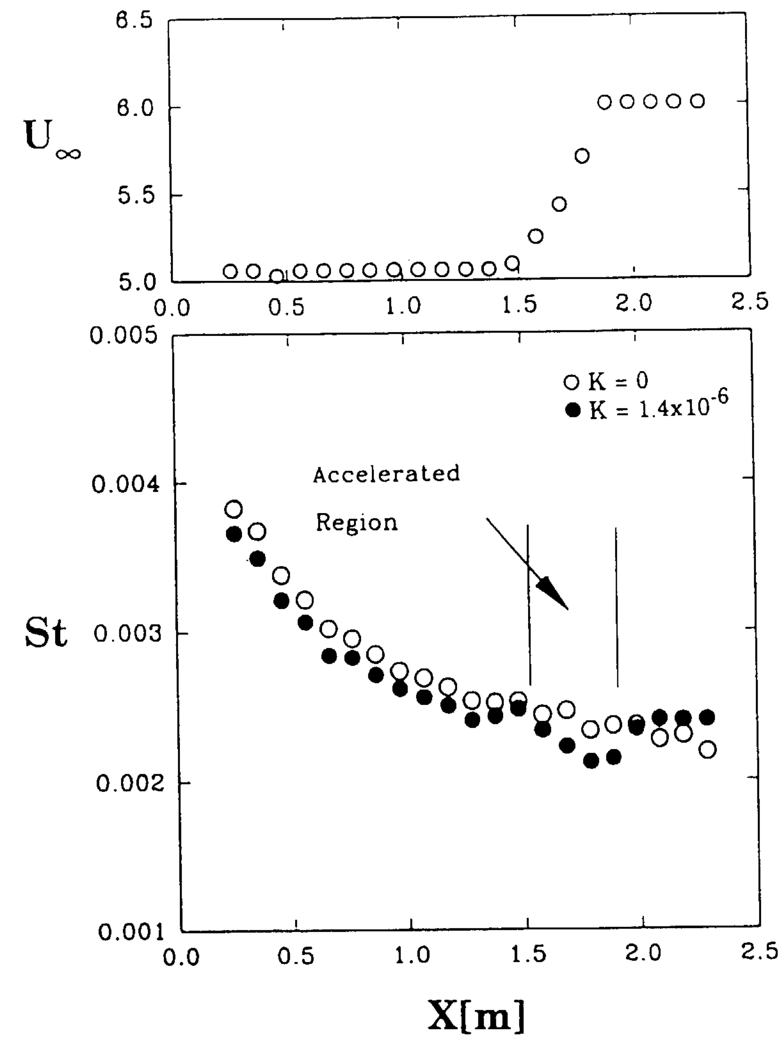

$K = 1.4 \times 10^{-6}$, $L/d_o = 4$, aerodynamically-smooth approaching flow

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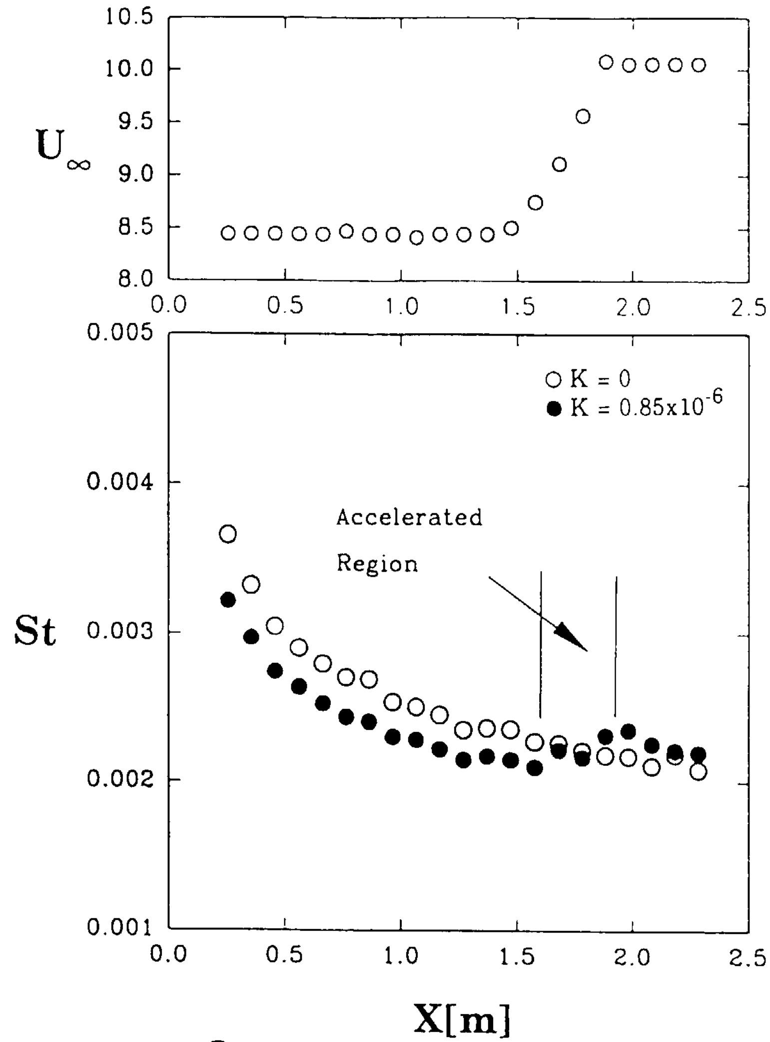

$K = 0.85 \times 10^{-6}$, $L/d_o = 4$, transitionally-rough approaching flow

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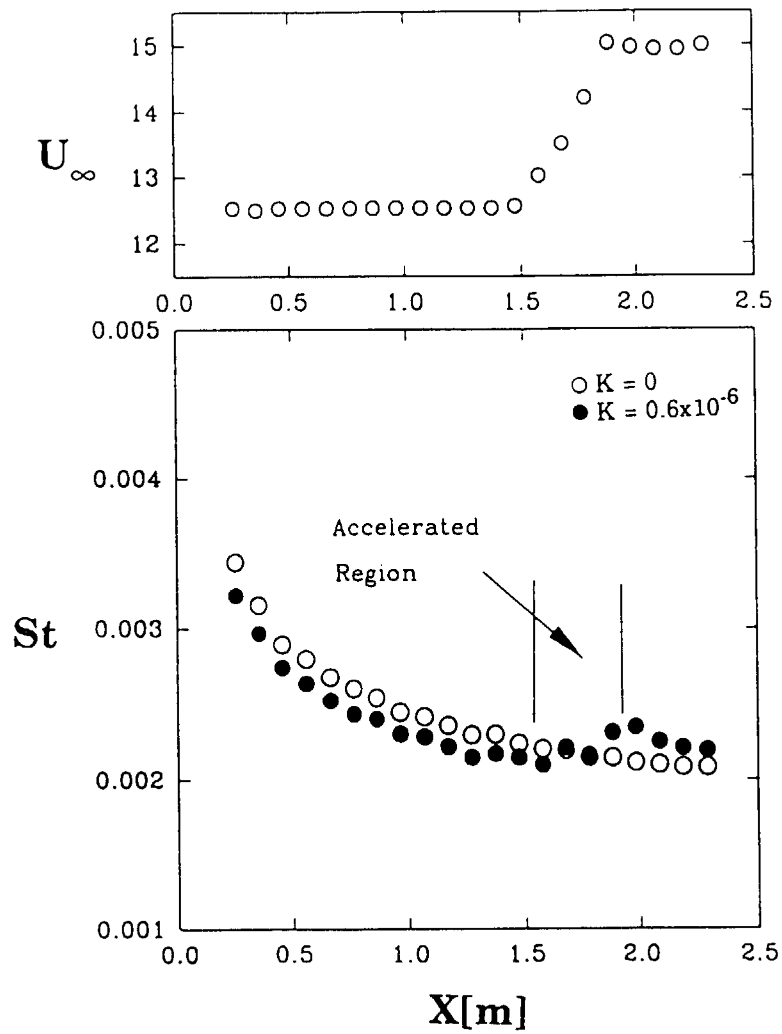

$K = 0.6 \times 10^{-6}$, $L/d_o = 4$, transitionally-rough approaching flow

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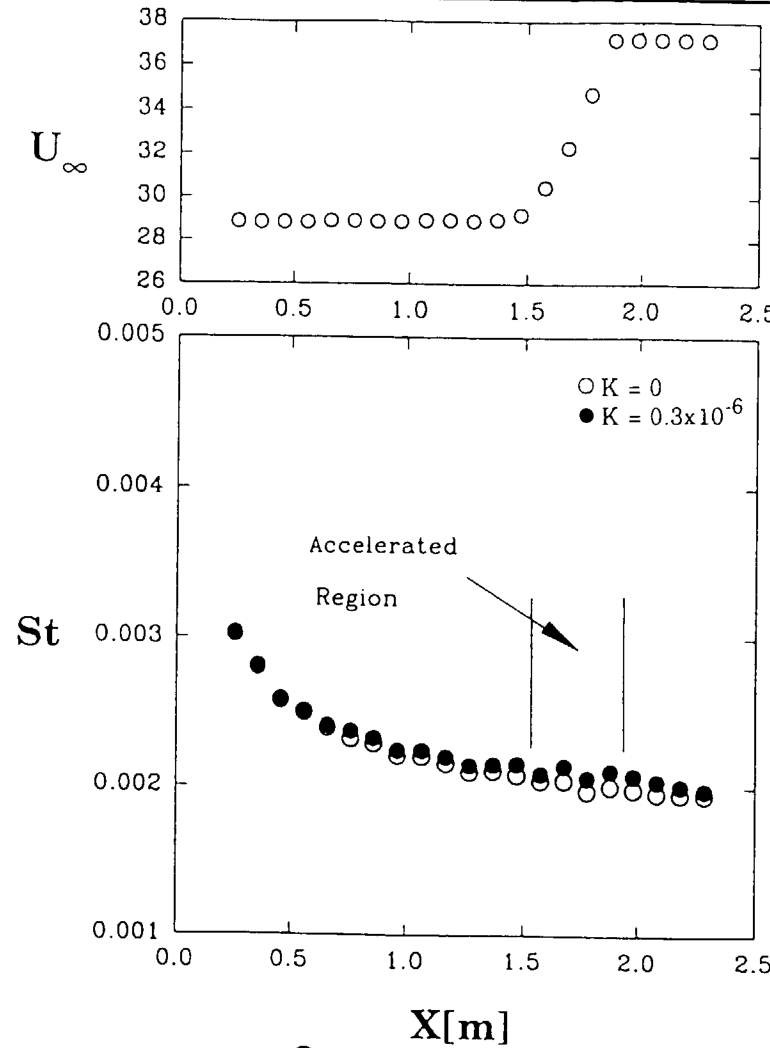

$K = 0.31 \times 10^{-6}$, $L/d_o = 4$, fully-rough approaching flow

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FLUID-FLOW DATA

$K \times 10^6$	U_∞ m/s	$L/d_o = 2$	$L/d_o = 4$
0.3	28	fully rough	fully rough
1.4	5	aero'ly smooth	aero'ly smooth

Roughness state based on the boundary layer conditions just upstream of the accelerated region.

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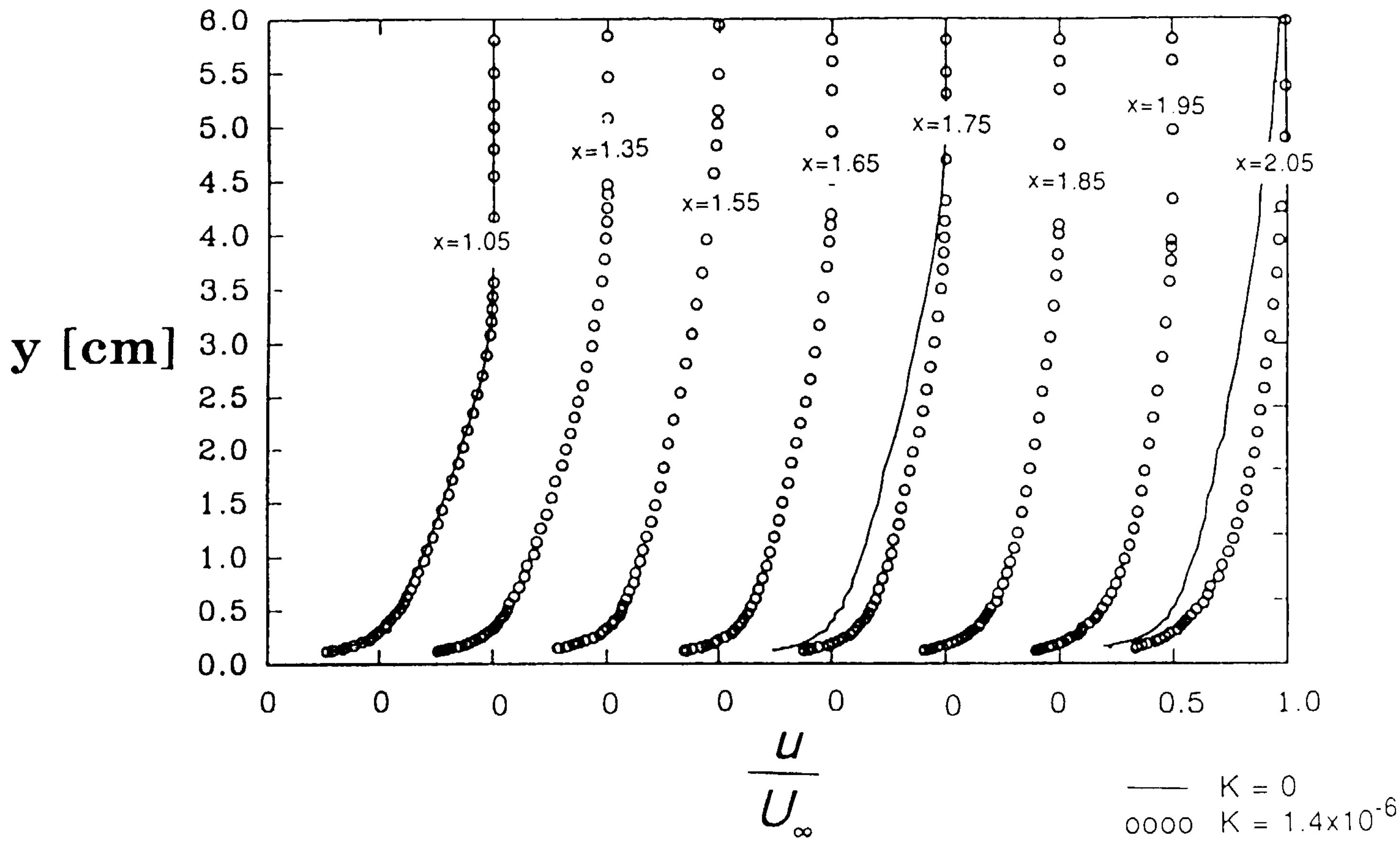

$K = 1.4 \times 10^{-6}$, $L/d_o = 2$, aerodynamically-smooth approaching boundary layer

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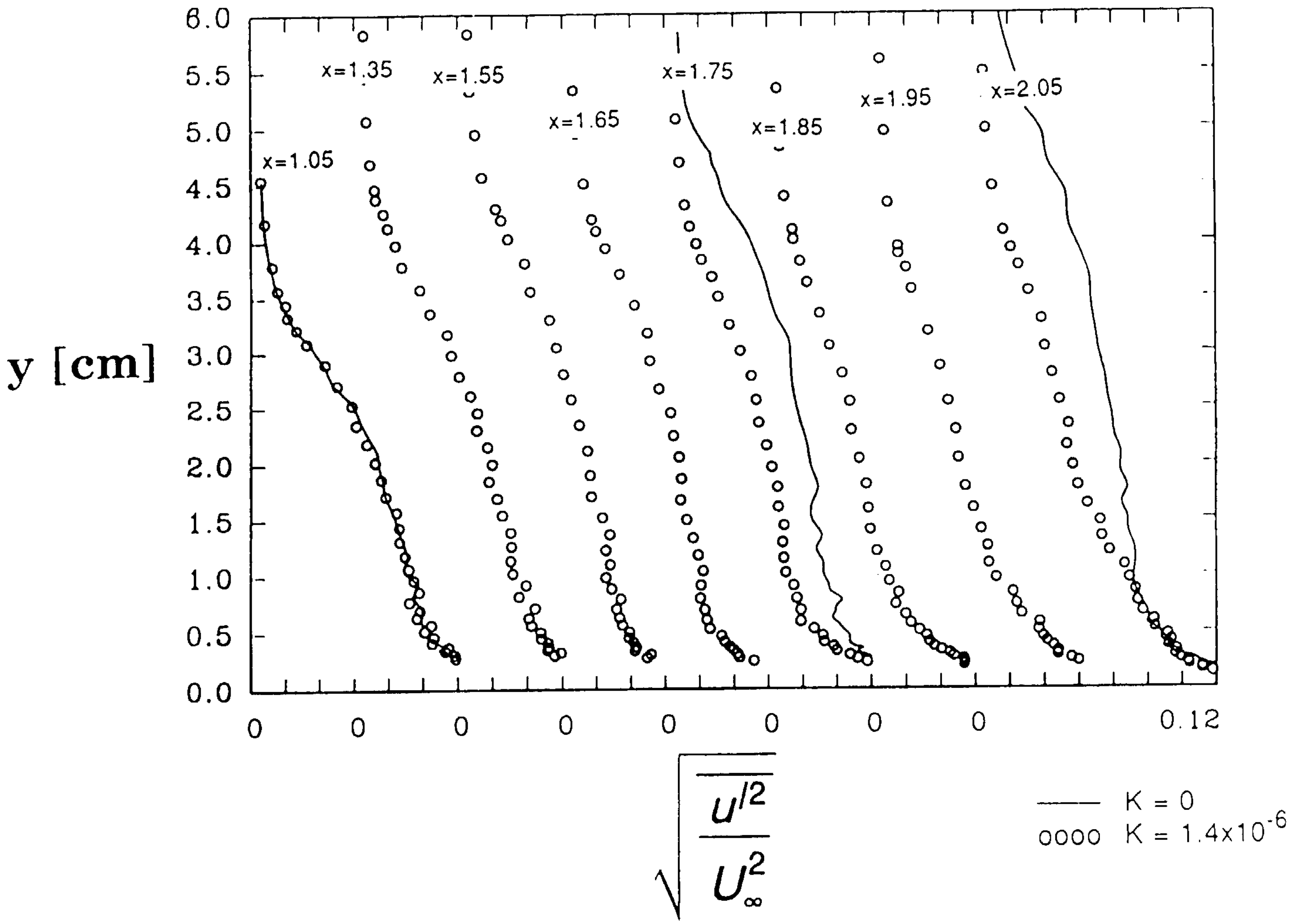

K = 1.4 X 10^{-6}, L/d_o = 2, aerodynamically-smooth approaching boundary layer

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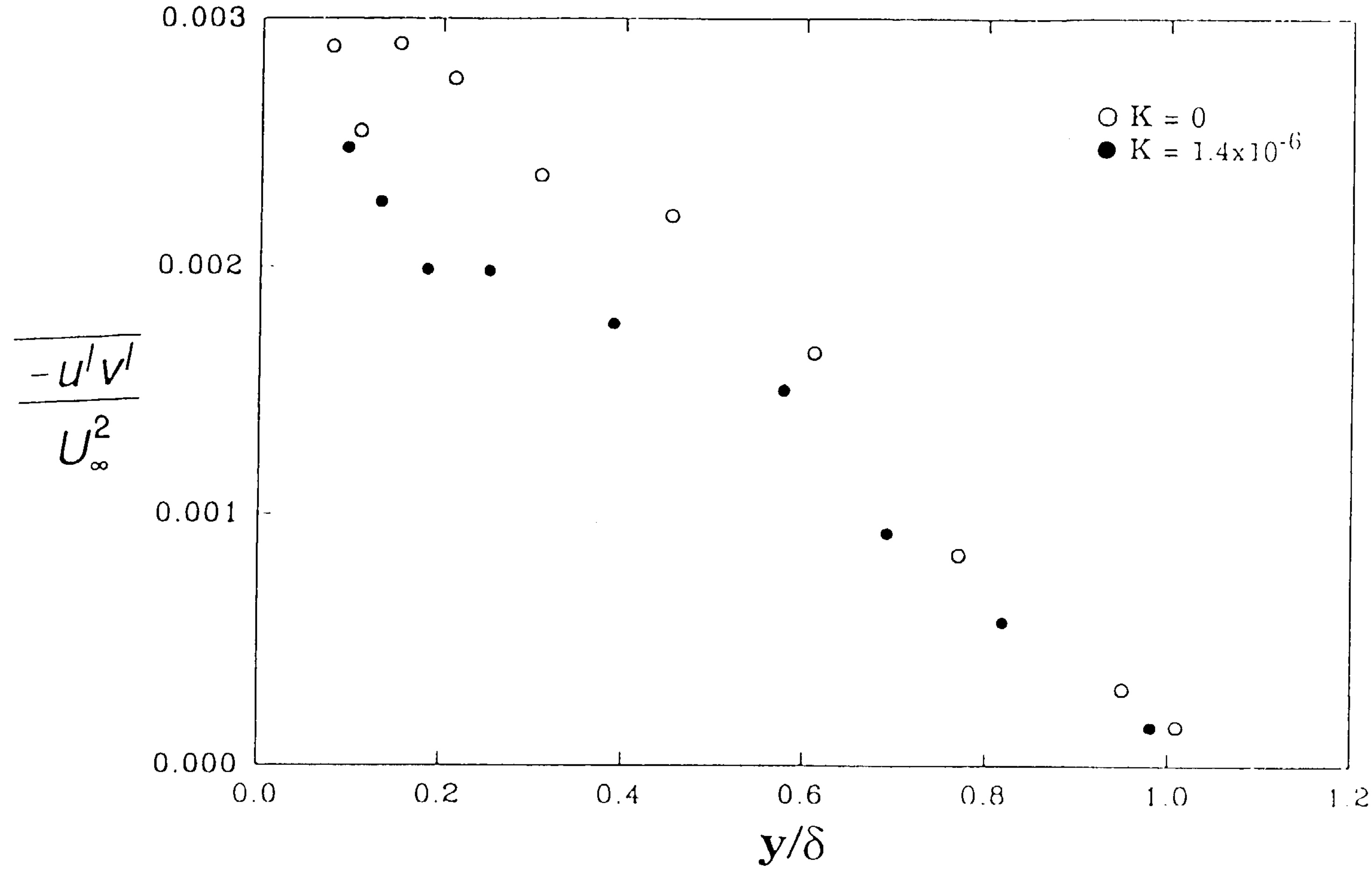

$K = 1.4 \times 10^{-6}$, $L/d_o = 2$, aerodynamically-smooth approaching boundary layer

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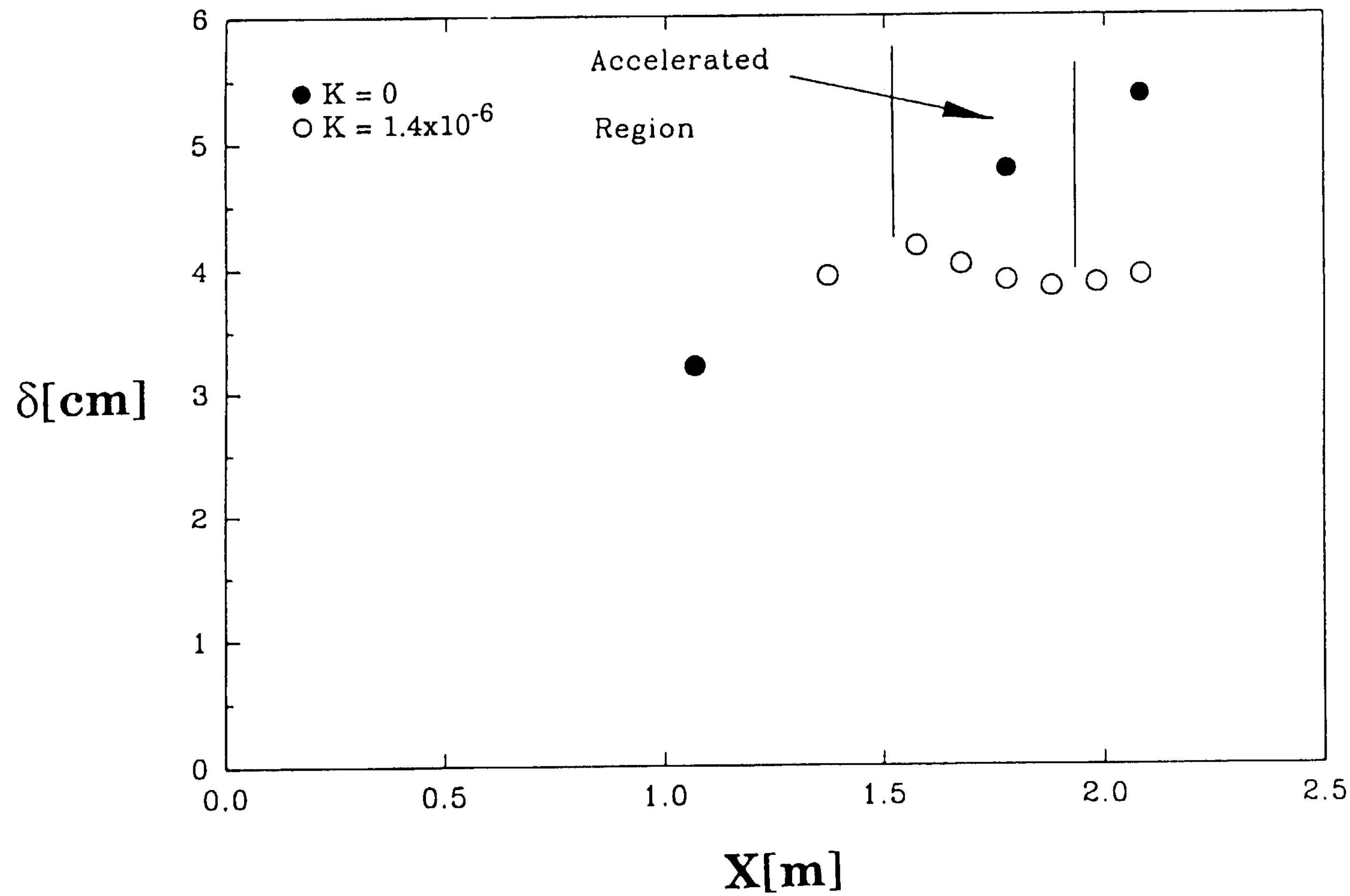

$K = 1.4 \times 10^{-6}$, $L/d_o = 2$, aerodynamically-smooth approaching boundary layer

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CONCLUSIONS

- Stanton numbers for fully-rough boundary layers increase with acceleration compared to zero-pressure gradient boundary layers.

- For the flows considered, roughness effects increased in the region of acceleration, indicating flow regime trend toward a rougher state when accelerated.

- For aerodynamically-smooth and transitionally-rough flows the effect of acceleration is not seen immediately at the beginning of the accelerated region as it is for fully-rough flows; however, as the boundary layer thins under acceleration, the surface becomes relatively rougher resulting in a sharp increase in Stanton number.

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CONCLUSIONS (Continued)

- After the acceleration, Stanton numbers return to the $K=0$ baseline case only for the fully-rough boundary layers. For the others, the Stanton numbers show a distinct shift indicating different roughness states upstream and down stream of the acceleration.

- Acceleration decreases the turbulent kinetic energy throughout the boundary layer for both the smooth and rough walls.

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REFERENCES

Chakroun, W., 1992, "Experimental Investigation of the Effects of Acceleration on Flow and Heat Transfer in the Turbulent Rough-Wall Boundary Layer," Ph. D. Dissertation, Department of Mechanical Engineering, Mississippi State University.

Coleman, H. W., 1976, "Momentum and Energy Transport in the Accelerated Fully Rough Turbulent Boundary Layer," Ph. D. Dissertation, Mechanical Engineering Department, Stanford University.

Kays, W. M. and Moffat, R. J., 1975, "The Behavior of Transpired Turbulent Boundary Layers," Report No. HMT-20, Thermosciences Division, Mechanical Engineering Department, Stanford University.

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