Int. J. Heat Mass Transfer. Vol. 36, No. 1, pp. 141–146, 1993
Printed in Great Britain

0017-9310/93 $5.00+0.00

The turbulent thermal boundary layer with an abrupt change from a rough to a smooth wall

ROBERT P. TAYLOR and J. KEITH TAYLOR
Thermal & Fluid Dynamics Laboratory, Mechanical and Nuclear Engineering Department, Mississippi State University, Mississippi State, MS 39762, U.S.A.

M. H. HOSNI
Department of Mechanical Engineering, Kansas State University, Manhattan, KS 66506, U.S.A.

and

HUGH W. COLEMAN
Propulsion Research Center, Mechanical Engineering Department, University of Alabama in Huntsville, Huntsville, AL 35899, U.S.A.

(*Received* 8 *July* 1991 *and in final form* 18 *February* 1992)

Abstract—The work reported here was motivated by concern over the use of smooth heat flux gages for heat transfer measurements on the otherwise rough turbine blades. Stanton number distributions and boundary layer profiles of mean temperature, mean velocity, and turbulence intensity are reported for a surface with a step change from a rough to a smooth surface. In most cases, the Stanton number immediately downstream of the change in roughness drops below the all-smooth-wall data at the same x-Reynolds number. The alignment of the smooth surface between the bases and crests of the roughness elements is shown to have only a weak effect on the Stanton number distribution. It is concluded that use of smooth heat flux gages on otherwise rough surfaces can cause large errors. It is recommended that heat transfer data collected in this manner be used with caution.

INTRODUCTION

IN THIS paper, the effects of a step change in surface roughness on heat transfer and fluid flow in the turbulent boundary layer are investigated experimentally. The primary motivation for undertaking the work reported here is to gain insight into the use of smooth heat flux gages to measure the external heat transfer rate on otherwise rough gas turbine engine blades. Inservice gas turbine blades can be very rough [1]. Also, blades are often covered with rough coatings. Of particular interest for this work are the Space Shuttle Main Engine fuel pump turbine blades which have rough coatings with an r.m.s. height of the order of 15 μm. This is very rough considering that the boundary layer thickness is of the order of 0.5 mm. Tests on these engine components are often conducted by installing small (about 1 mm in diameter) heat flux gages. These gages are usually much smoother than the surrounding rough surface.

Important early experimental work on flows with step changes in roughness was done in fully-developed channel flows by Jacobs [2]. One of the most comprehensive data sets was presented for zero pressure gradient boundary layer flows by Antonia and Luxton [3, 4]. They presented extensive velocity and turbulence measurements for both smooth-to-rough and rough-to-smooth step changes in surface roughness. They used rib-roughened surfaces where the rib crests on the rough part of the surface were aligned with the smooth section of the surface. Antonia and Luxton [5] reported similar experiments where the test surface consisted of a smooth section followed by a rib-roughened section with the bases of the ribs aligned with the smooth surface. This resulted in a smooth-to-rough transition with an upstanding roughness. Schofield [6] presented extensive flow measurements for step changes in surface roughness with adverse pressure gradient. Andreopoulos and Wood [7] reported extensive measurements of velocity profiles, turbulence quantities and skin friction distribution for flow over a smooth surface which was roughened in one narrow strip at about mid-plate using sandpaper. Their experiments modeled the effect of an impulse of roughness on the boundary layer flow. A good review of the literature is given by Smits and Wood [8]. All of the work referenced above was in the isothermal boundary layer and did not include heat transfer results.

In a previous paper [9], we reported preliminary experimental and computational results. However, interpretation of those results was limited by the

NOMENCLATURE

d_0	roughness element base diameter	$\overline{u'^2}$	turbulence intensity factor
$d(y)$	local roughness element diameter	U_∞	free stream velocity
k	roughness element height	x	axial distance from nozzle exit
L	roughness element spacing	y	coordinate normal to the wall surface
Re	Reynolds number	z	transverse coordinate.
St	Stanton number		
T	local fluid static temperature	Greek symbols	
T_∞	free stream static temperature	δ	boundary layer thickness
T_w	wall (plate) temperature	Δ	thermal boundary layer thickness
u	mean longitudinal velocity	Δ_2	enthalpy thickness.

coarse resolution of the Stanton number downstream of the rough-to-smooth interface. As discussed below, the Stanton numbers were determined by making an energy balance on individually heated test plates, resulting in a locally averaged Stanton number. The preliminary measurements were made with 0.1 m wide test plates. The experiments reported in this paper have been refined by replacing the first smooth test plate with four 0.025 m wide plates to better resolve the Stanton number distribution immediately downstream of the interface. Also, two alignments of the smooth portion of the surface were investigated—*base-aligned* as in Fig. 1(a) and *crest-aligned* as in Fig. 1(b).

In the following the experimental apparatus and measurements are briefly outlined and the results of the experiments are presented and discussed.

EXPERIMENTAL APPARATUS AND MEASUREMENTS

The experiments were performed in the Turbulent Heat Transfer Test Facility (THTTF), which is shown in Fig. 2. Complete descriptions of the facility and its qualification are presented in Coleman *et al.* [10] and Hosni *et al.* [11]. This facility is a closed loop wind tunnel with a free stream velocity range of 6–67 m s^{-1}. The temperature of the circulating air is controlled with an air to water heat exchanger and a cooling water loop. Following the heat exchanger the air flow is conditioned by a system of honeycomb and screens.

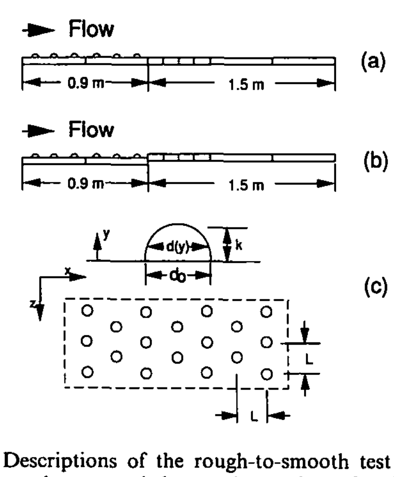

FIG. 1. Descriptions of the rough-to-smooth test surface, alignment schemes, and the roughness shape for the hemisphere roughened surface.

The bottom wall of the nominally 2.4 m long by 0.5 m wide by 0.1 m high test section consists of 24 electrically heated flat plates which are abutted together to form a continuous flat surface. Each nickel-plated aluminum plate (about 10 mm thick by 0.1 m in the flow direction) is uniformly heated from below by a custom-manufactured rubber-encased electric heater pad. Design computations showed that, with this configuration, a plate can be considered to be at a uniform temperature.

Figure 1 shows a schematic diagram for the test surface used in these experiments. The first 0.9 m of the test section surface were roughened with 1.27 mm diameter hemispheres, and the remaining 1.5 m length was smooth. The roughness elements were spaced two base diameters apart in a staggered array as shown in the figure. Immediately following the rough-to-smooth interface, four narrow 0.025 m wide test plates were used to better resolve the Stanton number in this region. Two alignments were considered—base-aligned as shown in Fig. 1(a) and crest-aligned as shown in Fig. 1(b).

The top wall can be adjusted to maintain a constant free stream velocity. An inclined water manometer with resolution of 0.06 mm is used to measure the pressure gradient during top wall adjustment. Static pressure taps are located in the side wall adjacent to

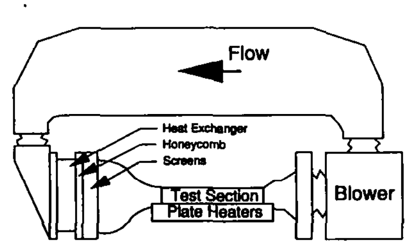

FIG. 2. Schematic of the Turbulent Heat Transfer Test Facility (THTTF).

each plate. The pressure tap located at the second plate is used as a reference, and the pressure difference between it and each other tap is minimized. For example, the maximum pressure difference for the 43 m s^{-1} case was 0.30 mm of water.

The boundary layer is tripped at the exit of the 19 : 1 area ratio nozzle with a 1 mm × 12 mm wooden strip. This trip location is immediately in front of the heated surface.

Stanton number determination

The Stanton number is determined using an energy balance on each of the individually heated plates. The Stanton number is computed from the definition using measured values of the plate heater power, plate temperature, free stream total temperature, and free stream velocity and experimentally calibrated models for the radiation loss and conduction to the support system. To minimize conduction losses the support rails are heated to approximately the same temperature as the plates. For the Stanton number data in this paper, the overall uncertainty, as discussed by Taylor *et al.* [12, 13], ranged from ±2% to ±5% for the 0.1 m wide plates and from ±4% to ±11% for the 0.025 m plates depending on flow conditions.

Profile measurements

The profiles of mean velocity, u, and longitudinal velocity fluctuation, $\overline{u'^2}$, were taken with a horizontal hot-wire. At each measurement position, 1000 instantaneous anemometer output voltage readings 0.01 s apart were taken and converted into velocities using a fourth order least squares calibration equation. The mean of the 1000 velocities was used as the mean velocity at that location, and the variance was taken as $\overline{u'^2}$. According to Coleman *et al.* [10], the overall uncertainties are ±2% for u and ±5% for $\overline{u'^2}$.

The mean temperature profiles were measured using a specially calibrated, butt-welded, chromel–constantan thermocouple probe. The overall uncertainty in the temperature measurement with this probe is quoted by Coleman *et al.* [10] to be ±0.08°C.

EXPERIMENTAL RESULTS

Experimental heat transfer and flow results have been obtained for zero pressure gradient, constant wall temperature and incompressible turbulent boundary layer flow in air with free stream velocities

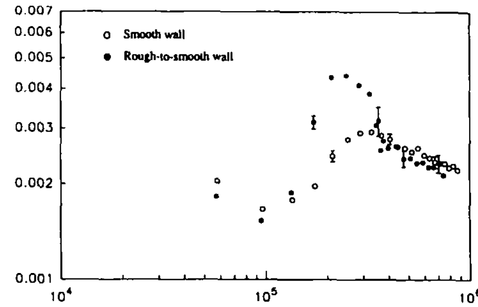

FIG. 3. Results of the Stanton number measurements plotted vs Re_x for U_∞ = 6 m s^{-1}—base-aligned.

of 6, 12, 27, 43, 58, and 66 m s^{-1} [12]. The corresponding x-Reynolds numbers ranged from 100 000 to 10 000 000. The x-Reynolds numbers immediately downstream of the rough-to-smooth interface ranged from 300 000 to 3 000 000. A representative subset of this data set is presented in this paper.

Figures 3 and 4 show plots of Stanton number vs x-Reynolds number for the base-aligned case. Also, the experimental Stanton number distributions for an all-smooth surface [10] are shown in the figures. These smooth-wall data were collected in the same experimental apparatus with the same instrumentation. While these smooth-wall data agree very well (±5%) with the usual smooth-wall correlations, they contain essentially the same bias error effects as the rough-to-smooth cases and are, therefore, the best choice for comparison.

Figure 3 shows the comparison for the U_∞ = 6 m s^{-1} case. In spite of the trip at the nozzle exit and the rough surface, the flow remains laminar for a considerable length. The flow becomes fully turbulent at an x-Reynolds number of about 200 000, and a transitionally rough boundary layer is established for a short distance before the rough-to-smooth interface. According to Hosni *et al.* [11], this case is transitionally rough† in the aerodynamic sense, while the higher velocity cases are fully rough boundary layers over the rough portion of the test surface. In the region between the rough-wall boundary layer and the developing smooth-wall boundary layer, the Stanton

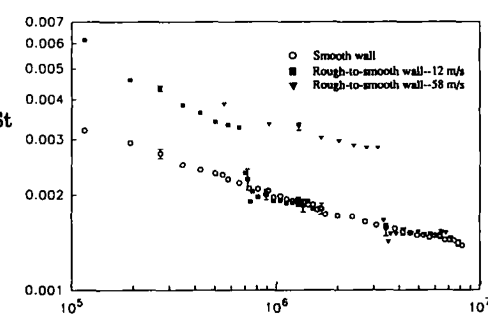

FIG. 4. Results of the Stanton number measurements plotted vs Re_x for U_∞ = 12 and 58 m s^{-1}—base-aligned.

† Turbulent flows that are influenced by surface roughness are usually divided into three regimes. Aerodynamically smooth flows are those where the roughness effects are so small that the flow behaves as if the wall were smooth. Fully rough flows are those where the roughness so dominates the momentum transport to the wall that viscous effects are negligible. In turbulent pipe flow fully rough flows are those where the friction factor is no longer a function of the Reynolds number. Transitionally rough flows occur at Reynolds numbers in between and both viscous and roughness effects are significant.

number decreases rapidly in a smooth, continuous fashion to the new smooth-wall condition.

Figure 4 shows the comparison for the $U_\infty = 12$ and 58 m s^{-1} cases. For both of these fully rough cases, the Stanton number drops immediately after the interface. There appears to be a slight dip in the rough-to-smooth Stanton number below the all-smooth Stanton number data. However, the uncertainty in the 0.025 m test plate Stanton number is too large to draw a definite conclusion at 12 m s^{-1}. At 58 m s^{-1} there is a definite dip in the Stanton number after the step change in surface roughness. The data at the free stream velocities of 27, 43, and 66 m s^{-1} showed the same trends as those in Fig. 4.

Overall, the transitionally rough flow has a smooth continuous change in Stanton number from the rough-surface region to the smooth-surface region. Fully rough cases, however, have an abrupt change in the Stanton number after the rough-to-smooth interface, with the Stanton numbers falling slightly below the equivalent all-smooth-wall values at the same x-Reynolds number. As the free stream velocity increases, the change becomes slightly more abrupt.

After the step change from rough to smooth, a smooth-wall layer develops inside the existing rough-wall layer. This smooth-wall layer eventually envelops the whole boundary layer. However, this new smooth-wall layer has a different virtual origin than the all-smooth boundary layer. Therefore, the comparisons based on equivalent x-Reynolds numbers may not be the most appropriate. An alternative presentation which eliminates the virtual origin problem is to base the comparison on the boundary layer enthalpy thickness Reynolds number. Figure 5 shows this comparison for the same 12 and 58 m s^{-1} base-aligned cases shown in Fig. 4. The enthalpy thicknesses were obtained for these zero pressure gradient, constant wall temperature boundary layers by direct integration of the Stanton number distributions. This viewpoint throws a different spin on the comparison. The dip does not go below the equivalent all-smooth case, and the 58 m s^{-1} case retains a very slight heat transfer augmentation. However, no important new insights are gained.

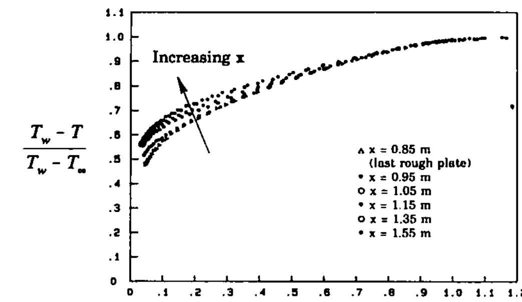

FIG. 6. Non-dimensional temperature profiles vs y/Δ for $U_\infty = 12$ m s^{-1}—base-aligned.

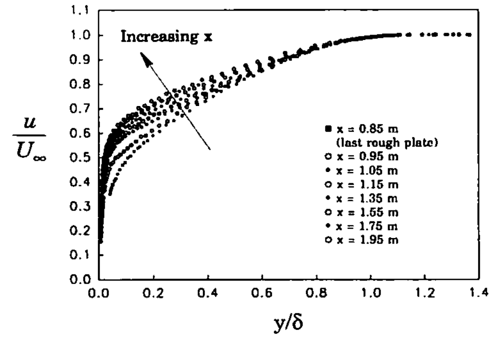

FIG. 7. Velocity profiles for the rough-to-smooth surface at increasing x-locations for $U_\infty = 12$ m s^{-1}—base-aligned.

Figures 6 and 7 show plots of the non-dimensional mean temperature profiles and mean velocity profiles for the base-aligned case with a free stream velocity of 12 m s^{-1}. The plots show that the profile immediately downstream of the rough-to-smooth interface quickly assumes smooth-wall characteristics in the near-wall region but resembles the rough-wall profile in the outer region. Further downstream of the step, the profiles gradually fill out to assume a smooth-wall-like shape. Profiles of axial turbulence intensity were also determined at the same locations downstream of the rough-to-smooth interface as the mean velocity profiles. Figure 8 shows the plot of these profiles for the 12 m s^{-1} case. The sharp near-wall peak typical of smooth-wall profiles is seen for all x-locations on

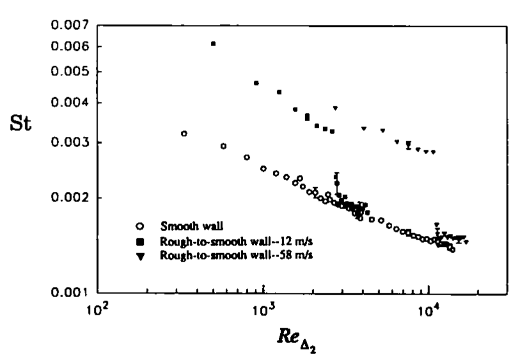

FIG. 5. Results of the Stanton number measurements plotted vs Re_{Δ_2} for $U_\infty = 12$ and 58 m s^{-1}—base-aligned.

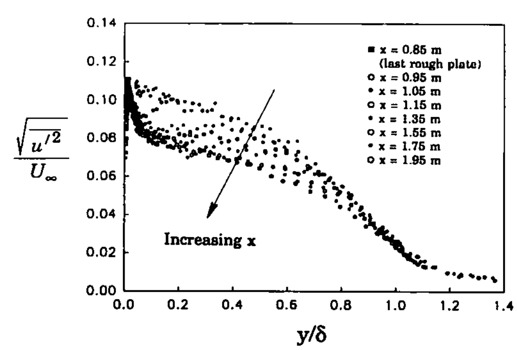

FIG. 8. Axial turbulence intensity profiles for the rough-to-smooth test surface at increasing x-locations for $U_\infty = 12$ m s^{-1}—base-aligned.

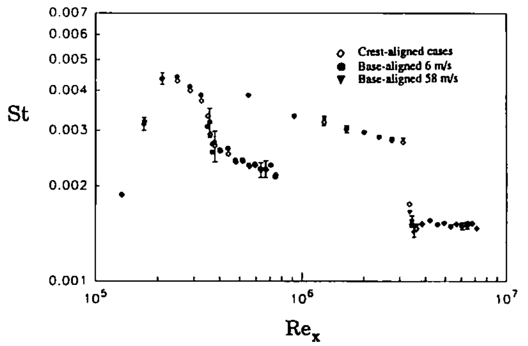

FIG. 9. Comparison of the Stanton number measurements for the base-aligned and crest-aligned cases at $U_\infty = 12$ and $58\ \mathrm{m\ s^{-1}}$.

the smooth portion of the test surface. The first smooth-portion profile at $x = 0.95$ m is particularly interesting. For $y/\delta > 0.2$, its behavior is typical of the rough wall, and for $y/\delta < 0.1$, its behavior is much more typical of the smooth wall.

The profiles shown in the preceding figures provide a possible explanation for why the Stanton number drops dramatically after the rough-to-smooth interface. Over the rough surface, the temperature and velocity profiles are greatly retarded when compared with the typical smooth-wall profiles. However, over the rough surface the net heat transfer is greatly augmented by direct transfer to the protruding roughness elements. Hosni *et al.* [11] estimate for the fully rough boundary layers with this rough surface that 65% of the net heat transfer is accounted for by direct transfer to the roughness elements, which account for only 33% of the total heat transfer surface area. When these retarded profiles move over the suddenly smooth surface they must rely on conduction through the sublayer for all of the heat transfer. If the gradients are retarded enough the heat transfer rate could be less than that of an equivalent all-smooth boundary layer.

A direct comparison of the Stanton number data for the two alignments at 6 and 58 $\mathrm{m\ s^{-1}}$ is shown in Fig. 9. For the 6 $\mathrm{m\ s^{-1}}$ case, the results are indistinguishable from each other within the data uncertainty. The data at the rough-to-smooth interface exhibit the same behavior for both the base-aligned and crest-aligned cases. This was also true for the 12 $\mathrm{m\ s^{-1}}$ case. For the 27 $\mathrm{m\ s^{-1}}$ case, the Stanton number for the crest-aligned case on the first 0.025 m smooth test plate was slightly larger than its base-aligned counterpart; however, there was a large overlap in the uncertainty intervals. For the 43, 58, and 66 $\mathrm{m\ s^{-1}}$ cases, as demonstrated for the 58 $\mathrm{m\ s^{-1}}$ case in the figure, the first crest-aligned Stanton number after the interface was slightly larger than its base-aligned equivalent with a small overlap in uncertainty intervals. This effect is not seen for any Stanton numbers further downstream regardless of the free stream velocity. For the conditions of these experiments, any effect of surface alignment is very small and observed only in the region immediately downstream of the step change in surface roughness. Mean velocity, mean temperature, and turbulence intensity profiles 0.05 m downstream of the interface at 12 $\mathrm{m\ s^{-1}}$ for the two alignments showed no measurable effect of the alignment. More information on the effects of the surface alignment can be found in the related paper by the present authors [14].

SUMMARY AND CONCLUSIONS

A step change in surface roughness from rough to smooth has been shown to have a dramatic effect on heat transfer in the turbulent boundary layer. For transitionally rough flow, the Stanton number after the rough-to-smooth interface quickly drops in a smooth, continuous fashion to the new smooth-wall equilibrium value. For fully rough flows, on the other hand, the Stanton number undergoes an immediate drop to a value at or below the equivalent smooth-wall Stanton number at the same x-Reynolds number. The boundary layer temperature profiles show the thermal boundary layer to slowly approach a smooth-wall equilibrium profile. Mean velocity and turbulence intensity profiles show the flow to rapidly assume smooth-wall behavior in the near-wall region, while requiring more distance to assume a complete smooth-wall behavior. The alignment of the rough-to-smooth surfaces shows only a very small effect on the heat transfer between the base-aligned and crest-aligned cases. Any effect that is observed between the two alignment cases is limited to the region immediately downstream of the rough-to-smooth interface.

For the particular application that initiated this research, these results indicate that the use of smooth surface heat flux gages to measure the heat transfer rate on otherwise rough surfaces could yield erroneous results. We recommend that heat flux data taken in this fashion be used with caution.

Acknowledgements—This research was supported by the NASA Lewis Research Center, Grant NAG 3 1116. The authors gratefully acknowledge the interest and encouragement of Mr Kestutis Civinskas of the Lewis Research Center.

REFERENCES

1. R. P. Taylor, Surface roughness measurements on gas turbine blades, *J. Turbomachinery* **112,** 175–180 (1990).
2. W. Jacobs, Umformung eines turbulenten Geschwindigkeitsprofiles, *Z. Angew. Math. Mech.* **19,** 87–100 (also NACA TM 951) (1939).
3. R. A. Antonia and R. E. Luxton, The response of a turbulent boundary layer to a step change in surface roughness. Part 2. Rough-to-smooth, *J. Fluid Mech.* **53,** 737–757 (1972).
4. R. A. Antonia and R. E. Luxton, The response of a turbulent boundary layer to a step change in surface roughness. Part 1. Smooth-to-rough, *J. Fluid Mech.* **48,** 721–726 (1971).
5. R. A. Antonia and R. E. Luxton, The response of a turbulent boundary layer to an upstanding step change in surface roughness, *J. Basic Engng* **93,** 22–23 (1971).

6. W. H. Schofield, Measurements in adverse-pressure-gradient turbulent boundary layers with a step change in surface roughness, *J. Fluid Mech.* **70**, 573–593 (1975).
7. J. Andreopoulos and D. H. Wood, The response of a turbulent boundary layer to a short length of surface roughness, *J. Fluid Mech.* **118**, 143–164 (1982).
8. A. J. Smits and D. H. Wood, The response of turbulent boundary layers to sudden perturbations, *Ann. Rev. Fluid Mech.* **17**, 321–358 (1985).
9. R. P. Taylor, J. K. Taylor, M. H. Hosni and H. W. Coleman, Heat transfer in the turbulent boundary layer with a step change in surface roughness, ASME Paper No. 91-GT-266, American Society of Mechanical Engineers, New York (1991).
10. H. W. Coleman, M. H. Hosni, R. P. Taylor and G. B. Brown, Smooth wall qualification of a turbulent heat transfer test facility, Report TFD-88-2, Mech. and Nucl. Engng Dept., Mississippi State University, Mississippi (1988).
11. M. H. Hosni, H. W. Coleman and R. P. Taylor, Measurements and calculations of rough-wall heat transfer in the turbulent boundary layer, *Int. J. Heat Mass Transfer* **34,** 1067–1082 (1991).
12. J. K. Taylor, R. P. Taylor, M. H. Hosni and H. W. Coleman, An investigation on the influence of a step change in surface roughness on turbulent flow and heat transfer, Report TFD-91-1, Mech. and Nucl. Engng Dept., Mississippi State University, Mississippi (1991).
13. J. K. Taylor, R. P. Taylor and H. W. Coleman, Using uncertainty analysis to guide and evaluate modifications of a boundary layer heat transfer test facility. In *Fundamental Experimental Measurements in Heat Transfer*, HTD Vol. 179, pp. 41–48. American Society of Mechanical Engineers, New York (1991).
14. R. P. Taylor, J. K. Taylor, M. H. Hosni and H. W. Coleman, Investigation of surface alignment effects on turbulent boundary-layer heat transfer for a step change in surface roughness. In *Mixed Convection Heat Transfer*, HTD Vol. 163, pp. 103–109. American Society of Mechanical Engineers, New York (1991).