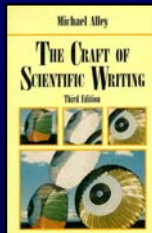


# Formatting a Document in Scientific Writing

These slides, which are used in graduate and undergraduate engineering courses at Virginia Tech, come from Chapter 16 in *The Craft of Scientific Writing* (3rd ed., Springer-Verlag).



# Formatting a Document in Scientific Writing

## HIGH FREESTREAM TURBULENCE EFFECTS ON ENDWALL HEAT TRANSFER FOR A GAS TURBINE STATOR VANE

R. W. Radomsky\* and K. A. Thole  
Mechanical Engineering Department  
Virginia Polytechnic Institute and State University  
Blacksburg, Virginia 24060

### ABSTRACT

High freestream turbulence along a gas turbine airfoil and strong secondary flows along the endwall have both been reported to significantly increase convective heat transfer. This study superimposes high freestream turbulence on the naturally occurring secondary flow vortices to determine the effects on the flowfield and the endwall convective heat transfer. Measured flowfield and heat transfer data were compared between low freestream turbulence levels (0.0%) and conditions at several turbulence levels (5–5%) that were generated using an active grid. These experiments were conducted using a scaled-up, first stage stator vane geometry. Infrared thermography was used to measure surface temperatures on a constant heat flux plate placed on the endwall surface. Laser Doppler velocimeter (LDV) measurements were performed at all three components of the mean and fluctuating velocities of the leading edge vortex flow vortices. The results indicate that the mean flowfields for the leading edge horseshoe vortex were similar between the low and high freestream turbulence cases. High turbulence levels in the leading edge-endwall junction were attributed to a vortex breakdown for both the low and high freestream turbulence cases. While, in general, the high freestream turbulence increased the endwall heat transfer, low magnitudes were found to coincide with the regions having the most intense vortex motions.

### INTRODUCTION

Along a turbine airfoil surface, elevated convective heat transfer coefficients occur as a result of high turbulence levels entering a combustor in a gas turbine engine. The platform of an airfoil (endwall), a critical surface where durability can be an issue, also has high convective heat transfer levels with a complex footprint. The complexity occurs from the secondary flows that develop in the form of vortices that envelop the platform surface. Both of these effects, high freestream turbulence effects on airfoil heat transfer and secondary flow effects on endwall heat transfer, have been discussed in the literature. When mixing flows the literature on the combined effects of both low-level freestream turbulence and secondary flows on endwall heat transfer

Turbulence measurements taken at the exit of a variety of gas turbine combustors have shown that the levels can range between 3% and 40% (Goldstein, et al., 1983; Kuznetsov and McMurtry, 1989; and Goddard, et al., 1993) with some indication that the integral length scale scales with the diameter of the dilution holes in the combustor (Mois, 1992). As these high levels progress through the downstream turbine vane passage, there is a production of turbulence resulting in high turbulent kinetic energy levels at the exit of the passage (Radomsky and Thole, 1999). The effect of these high turbulence levels has on the airfoil itself is to significantly increase the heat transfer along the leading edge and pressure side surfaces as well as move the transition location forward on the suction side surface.

The secondary flow previously mentioned takes the form of a leading edge horseshoe vortex. This vortex spins into a sea leg that wraps around the suction surface and another leg that wraps around the pressure surface with the latter ultimately forming a passage vortex. As the flow progresses downstream, the flow is dominated by the passage vortex. Gargler and Russell (1984) identified, through flow visualization and surface heat transfer, that high convective heat transfer coefficients coincided with the most intense vortex action. King and Thole (1999) showed through flowfield and heat transfer measurements that the peak heat transfer coincided with the downward legs of both the horseshoe vortex and passage vortex. The downward leg of these vortices brings high speed freestream fluid towards the endwall and thus the boundary layer is ultimately increased the local heat transfer coefficients. As seen in several past endwall heat transfer studies (Cianci, et al., 1989; and Boyle and Russell, 1990; King, et al., 1999) the peak heat transfer on the passage endwall escape from the pressure side of the airfoil to the suction side of the adjacent airfoil as the passage vortex moves in that direction.

Although there have been a number of studies documenting high freestream turbulence effects on airfoil heat transfer and there have been a number of endwall flowfield and heat transfer studies, there are no studies documenting endwall heat transfer at combustor level freestream turbulence. The work presented in this paper investigates the effect that high turbulence has on endwall heat transfer. In particular, one of the regions having the highest heat transfer is the leading edge-endwall junction. Three-dimensional flowfield mea-

(U) and pitchwise (P) components through the top endwall; and the streamwise (U) and spanwise (W) components through the sidewall. Coincident measurements were made through the sidewall to quantify the Reynolds shear stress,  $\tau_{xy}$ . The probe volume length and diameter for the 750 mm lens with the beam separator were 0.85 mm and 72 microns. The data were corrected for velocity bias effects by applying incidence time weighting.

### Endwall Heat Transfer Measurements

The heat transfer results for the high freestream turbulence conditions were measured in the same facility as for the low freestream turbulence conditions (King, et al., 1999). These measurements were obtained with a constant heat flux plate placed on the bottom endwall, as indicated by the cross-hatched area in Figure 1, surrounding the 50-degree stator vane. The constant heat flux plate consisted of a 50 micron thick copper layer on top of a 75 micron thick kapton layer in which 25 micron thick incand heating elements were embedded in a serpentine pattern. This heater was placed onto a 1.9 cm thick wood surface using double-sided tape. Just below the wood was a 2.54 cm thick R-5 extruded Styrofoam board. The total heating area for the plate was 0.540 m<sup>2</sup> and the input power was adjusted to give a heat flux of 980 W/m<sup>2</sup>. The lateral convection was estimated to be less than 1% within the averaging spot size for the infrared camera. The top surface of the heater plate was painted black giving an emissivity of 0.94.

Surface temperature data was acquired using a calibrated infra-red camera (Inframetrics Model 790). The camera was calibrated in situ using type E ribbon thermocouples that were painted black and placed on the heated surface. The calibration procedure was performed to obtain the correct plate emissivity and background temperature and insure a linear relationship between the infra-red camera measurements and the thermocouple reading over the required operating temperature range. To perform these measurements, the top endwall was replaced with a plate having 13 viewing ports in which an 11.43 cm diameter crystal fluoride window or, when not making measurements from that port, a lens insert could be placed. Each endwall temperature resulted from an average of 16 images and, based on an uncertainty analysis, it was determined that five of these 16-averaged images were enough to get a good average. Small positioning crosses were placed on the endwall to identify where each of the 13 images were relative to the turbine vane. An in-house processing routine allowed the 13 images to be assembled into one complete endwall temperature distribution. The infrared camera performed a spatial averaging over 0.37 cm and operated at its maximum viewing area of 21.5 cm by 16 cm represented by 255 by 206 pixels.

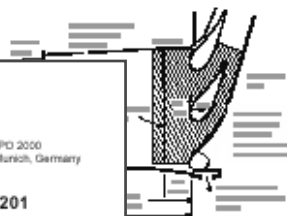
The input heat flux was corrected for radiation losses, which amounted to between 7–23 % of the input power, and conduction losses, which amounted to 1.7–3.5 % of the input power. No correction was necessary regarding heat losses from conduction to the turbine vane itself because the vane was constructed using Styrofoam. Using the measured temperatures and the remaining convective heat flux, the heat transfer coefficients were computed and reported as Stanton numbers.

### UNCERTAINTY ESTIMATED

The partial derivatives and sequential perturbation methods, described by Moffat (1988), were used to estimate the uncertainties of the measured values. Uncertainties were calculated based on a 95% confidence interval. For each velocity component 15,000 data points were used to compute the mean and turbulence quantities; whereas when coincident data was acquired 20,000 data points were acquired. The relative of the end wall convective uncertainties for the mean velocities were 3% while the precision of the raw velocities was 2.1% for  $u_{rms}$ , 1.7% for the  $v_{rms}$  and

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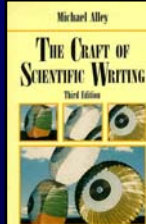
Location	U (m/s)	V (m/s)	W (m/s)	Turbulence (%)
Top Endwall	10.0	0.0	0.0	5.0
Side Wall	10.0	0.0	0.0	5.0
Pressure Side	10.0	0.0	0.0	5.0
Suction Side	10.0	0.0	0.0	5.0
Endwall Junction	10.0	0.0	0.0	5.0

Fig. 1 Test section containing the

endwall heat transfer measurement section, described in detail by Radomsky and Thole (1999). The flow is from left to right. The low square bars with jets injecting into the endwall are used to generate the high turbulence levels. The flow is from left to right. The low square bars with jets injecting into the endwall are used to generate the high turbulence levels. The flow is from left to right. The low square bars with jets injecting into the endwall are used to generate the high turbulence levels.

in a plane at the endwall-vane junction that intersects the stagnation is chosen to compare with that position at low turbulence conditions. The optic LDV system used in this study conjunction with a TSI model 9200 if data was processed using TSI model software. U, V, and W were measured with a probe (LDV) positioned in two different locations with a beam expander was used on side measurements of the streamwise

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## Reports

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Figure 1

Table 1

equation 1

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Fig. 1

Table 1

equation (1)

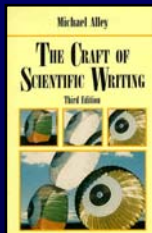
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fig. 1

table 1

Eq. 1



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## HIGH FREESTREAM TURBULENCE EFFECTS ON ENDWALL HEAT TRANSFER FOR A GAS TURBINE STATOR VANE

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### ABSTRACT

High freestream turbulence along a gas turbine airfoil and strong secondary flows along the endwall have both been reported to significantly increase convective heat transfer. This study superimposes high freestream turbulence on the naturally occurring secondary flow vortices to determine the effects on the flowfield and the endwall convective heat transfer. Measured flowfield and heat transfer data were compared between low freestream turbulence levels (0.0%) and combustor simulated turbulence levels (19.5%) that were generated using an active grid. These experiments were conducted using a scaled-up, first stage stator vane geometry. Infrared thermography was used to measure surface temperatures on a constant heat flux plate placed on the endwall surface. Laser Doppler velocimeter (LDV) measurements were performed of all three components of the mean and fluctuating velocities of the leading edge horseshoe vortex. The results indicate that the mean flowfields for the leading edge horseshoe vortex were similar between the low and high freestream turbulence cases. High turbulence levels in the leading edge-endwall juncture were attributed to a vortex meandering for both the low and high freestream turbulence cases. While, in general, the high freestream turbulence increased the endwall heat transfer, low augmentations were found to coincide with the regions having the most intense vortex motions.

### INTRODUCTION

Along a turbine airfoil surface, elevated convective heat transfer coefficients occur as a result of high turbulence levels entering a gas turbine engine. The platform of an airfoil (endwall), a critical surface where durability can be an issue, also has high convective heat transfer levels with a complex footprint. The complexity occurs from the secondary flows that develop in the form of vortices that sweep the platform surface. Both of these effects, high freestream turbulence effects on airfoil heat transfer and secondary flow effects on endwall heat transfer, have been discussed in the literature. What is missing from the literature is the combined effects of combustor level freestream turbulence and secondary flows on endwall heat transfer.

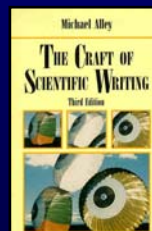
Turbulence measurements taken at the exit of a variety of gas turbine combustors have shown that the levels can range between 0% and 40% (Goldstein, et al., 1983; Kuo and McDurk, 1989; and Cosbell, et al., 1993) with some indication that the integral length scale scales with the diameter of the dilution holes in the combustor (Moss, 1992). As these high levels progress through the downstream turbine vane passage, there is a production of turbulence resulting in high turbulent kinetic energy levels at the exit of the passage (Radomsky and Thole, 1999). The effect that these high turbulence levels has on the airfoil itself is to significantly increase the heat transfer along the leading edge and pressure side surfaces as well as move the transition location forward on the suction side surface.

The secondary flows previously mentioned take the form of a leading edge horseshoe vortex. This vortex splits into one leg that wraps around the suction surface and another leg that wraps around the pressure surface with the latter ultimately forming a passage vortex. As the flow progresses downstream, the flow is dominated by the passage vortex. Gaugler and Russell (1984) identified, through flow visualization and surface heat transfer, that high convective heat transfer coefficients coincided with the most intense vortex action. Kang and Thole (1999) showed through flowfield and heat transfer measurements that the peak heat transfer coincided with the downward legs of both the horseshoe vortex and passage vortex. The downward leg of these vortices brings high speed freestream fluid towards the endwall and thins the boundary layer to ultimately increase the local heat transfer coefficients. As seen in several past endwall heat transfer studies (Cheriani, et al., 1980; and Boyle and Russell, 1990; Kang, et al., 1999) the peak heat transfer on the passage endwall sweeps from the pressure side of the airfoil to the suction side of the adjacent airfoil as the passage vortex moves in that direction.

Although there have been a number of studies documenting high freestream turbulence effects on airfoil heat transfer and there have been a number of endwall flowfield and heat transfer studies, there are no studies documenting endwall heat transfer at combustor level freestream turbulence. The work presented in this paper investigates the effect that high turbulence has on endwall heat transfer. In particular, one of the regions having the highest heat transfer is the leading edge-endwall juncture. Three-dimensional flowfield mea-

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layout



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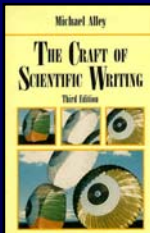
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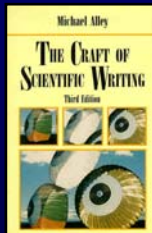
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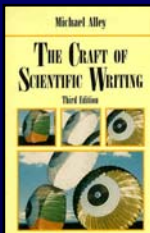
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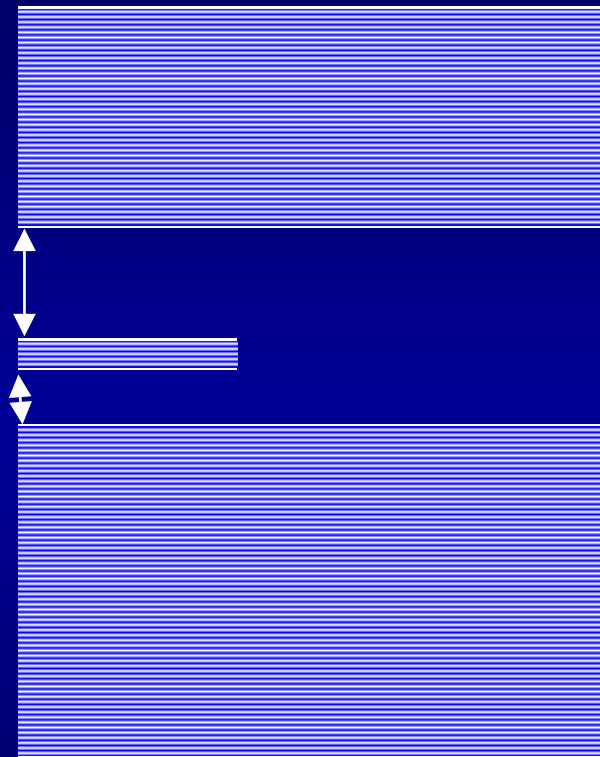
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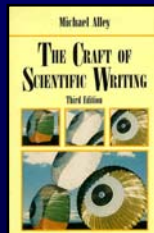
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### INTRODUCTION

Along a turbine airfoil surface, elevated convective heat transfer coefficients occur as a result of high turbulence levels entering a combustor in a gas turbine engine. The platform of an airfoil (endwall), a critical surface where durability can be an issue, also has high convective heat transfer levels with a complex footprint. The complexity occurs from the secondary flows that develop in the form of vortices that envelop the platform surface. Both of these effects, high freestream turbulence effects on airfoil heat transfer and secondary flow effects on endwall heat transfer, have been discussed in the literature. When measuring flow fields in the combined effects of low to high freestream turbulence and secondary flows on endwall heat transfer:

Turbulence measurements taken at the exit of a variety of gas turbine combustors have shown that the levels can range between 3% and 40% (Goldstein, et al., 1983; Kuetzen and McDirk, 1980; and Goddard, et al., 1993) with some indication that the integral length scale scales with the diameter of the dilution holes in the combustor (Mois, 1992). As these high levels progress through the downstream turbine vane passage, there is a production of turbulence resulting in high turbulent kinetic energy levels at the exit of the passage (Radomsky and Thole, 1999). The effect of these high turbulence levels has on the airfoil itself is to significantly increase the heat transfer along the leading edge and pressure side surfaces as well as move the transition location forward on the suction side surface.

The secondary flows previously mentioned take the form of a leading edge horseshoe vortex. This vortex splits into two legs that wrap around the suction surface and another leg that wraps around the pressure surface with the latter ultimately forming a passage vortex. As the flow progresses downstream, the flow is dominated by the passage vortex. Gargler and Russell (1984) identified, through flow visualization and surface heat transfer, that high convective heat transfer coefficients coincided with the most intense vortex action. King and Thole (1999) showed through flowfield and heat transfer measurements that the peak heat transfer coincided with the downward legs of both the horseshoe vortex and passage vortex. The downward legs of these vortices bring high speed freestream fluid towards the endwall and thus the boundary layer is ultimately increased the local heat transfer coefficients. As seen in several past endwall heat transfer studies (Ciccarelli, et al., 1980; and Boyle and Russell, 1990; King, et al., 1999) the peak heat transfer on the passage endwall escape from the pressure side of the airfoil to the suction side of the adjacent airfoil as the passage vortex meanders in that direction.

Although there have been a number of studies documenting high freestream turbulence effects on airfoil heat transfer and these have been a number of endwall flowfield and heat transfer studies, there are no studies documenting endwall heat transfer at combustor level freestream turbulence. The work presented in this paper investigates the effect that high turbulence has on endwall heat transfer. In particular, one of the regions having the highest heat transfer is the leading edge-endwall junction. Three-dimensional flowfield mea-

surements ( $U$ ) and pitchwise ( $Z$ ) components through the top endwall; and the streamwise ( $U$ ) and spanwise ( $W$ ) components through the sidewall. Coincident measurements were made through the sidewall to quantify the Reynolds shear stress,  $\tau_{xy}$ . The probe volume length and diameter for the 750 mm lens with the beam separator were 0.85 mm and 72 microns. The data were corrected for velocity bias effects by applying incidence time weighting.

### Endwall Heat Transfer Measurements

The heat transfer results for the high freestream turbulence conditions were measured in the same facility as for the low freestream turbulence conditions (King, et al., 1999). These measurements were obtained with a constant heat flux plate placed on the bottom endwall, as indicated by the cross-hatched area in Figure 1, surrounding the 50% chord stator vane. The constant heat flux plate consisted of a 50 micron thick copper layer on top of a 75 micron thick kapton layer in which 25 micron thick incand heating elements were embedded in a serpentine pattern. This heater was placed onto a 1.9 cm thick wood surface using double-sided tape. Just below the wood was a 2.54 cm thick R-5 extruded Styrofoam board. The total heating area for the plate was 0.540 m<sup>2</sup> and the input power was adjusted to give a heat flux of 980 W/m<sup>2</sup>. The lateral convection was estimated to be less than 1% within the averaging spot size for the infrared camera. The top surface of the heater plate was painted black giving an emissivity of 0.94.

Surface temperature data was acquired using a calibrated infra-red camera (Inframetrics Model 790). The camera was calibrated in situ using type E ribbon thermocouples that were painted black and placed on the heated surface. The calibration procedure was performed to obtain the correct plate emissivity and background temperature and insure a linear relationship between the infra-red camera measurements and the thermocouple reading over the required operating temperature range. To perform these measurements, the top endwall was replaced with a plate having 13 viewing ports in which an 11.43 cm diameter crystal fluoride window or, when not making measurements from that port, a lens insert could be placed. Each endwall temperature resulted from an average of 16 images and, based on an uncertainty analysis, it was determined that five of these 16-averaged images were enough to get a good average. Small positioning crosses were placed on the endwall to identify where each of the 13 images were relative to the turbine vane. An in-house processing routine allowed the 13 images to be assembled into one complete endwall temperature distribution. The infra-red camera performed a spatial averaging over 0.37 cm and operated at its maximum viewing area of 21.5 cm by 16 cm represented by 255 by 206 pixels.

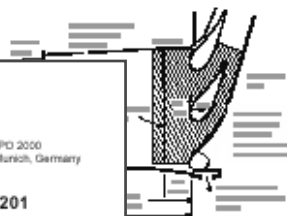
The input heat flux was corrected for radiation losses, which amounted to between 7-23 % of the input power, and conduction losses, which amounted to 1.7-3.5 % of the input power. No correction was necessary regarding heat losses from conduction to the turbine vane itself because the vane was constructed using Styrofoam. Using the measured temperatures and the remaining convective heat flux, the heat transfer coefficients were computed and reported as Stanton numbers.

### UNCERTAINTY ESTIMATED

The partial derivatives and sequential perturbation methods, described by Moffat (1988), were used to estimate the uncertainties of the measured values. Uncertainties were calculated based on a 95% confidence interval. For each velocity component 15,000 data points were used to compute the mean and turbulence quantities; whereas when coincidence data was acquired 20,000 data points were acquired. The relative of the mean and turbulence uncertainties for the mean velocities were 3% while the precision of the raw velocities was 2.1% for  $u_{rms}$ , 1.7% for the  $v_{rms}$  and

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Location	U (m/s)	V (m/s)	W (m/s)	U' (m/s)	V' (m/s)	W' (m/s)	xy (N/m <sup>2</sup> )
1	10.0	0.0	0.0	0.5	0.0	0.0	0.0
2	10.0	0.0	0.0	0.5	0.0	0.0	0.0
3	10.0	0.0	0.0	0.5	0.0	0.0	0.0
4	10.0	0.0	0.0	0.5	0.0	0.0	0.0
5	10.0	0.0	0.0	0.5	0.0	0.0	0.0
6	10.0	0.0	0.0	0.5	0.0	0.0	0.0
7	10.0	0.0	0.0	0.5	0.0	0.0	0.0
8	10.0	0.0	0.0	0.5	0.0	0.0	0.0
9	10.0	0.0	0.0	0.5	0.0	0.0	0.0
10	10.0	0.0	0.0	0.5	0.0	0.0	0.0
11	10.0	0.0	0.0	0.5	0.0	0.0	0.0
12	10.0	0.0	0.0	0.5	0.0	0.0	0.0
13	10.0	0.0	0.0	0.5	0.0	0.0	0.0

Fig. 1 Test section containing the

test section containing the stator, described in detail by Radomsky et al. (1999). The high turbulence levels. The low square bars with jets injecting into and downstream directions. The holes having a diameter of 1.5 mm. These hollow bars were arranged 88 mm staggered position or, in terms of front of the stagnation position. A 1% that applied each of the bars. The velocity grid was 10.5% measured at 0.13 cm location. The integral length scale 0.12 and was uniform across the span of the airfoil. The flow quality will be given

in a plane at the endwall-vane junction region that intersects the stagnation as shown to compare with that provided at low turbulence conditions. The optic LDV system used in this study conjunction with a TSI model 9200 data was processed using TSI model controlled using TSI's PIND software.  $U$ ,  $V$ , and  $W$  were measured with a two-beam (LDV) positioned in two different locations with a beam expander was used on side measurements of the streamwise

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