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ABSTRACT

An approach to predicting turbine blade heat transfer when turbulent flow relaminarizes due to strong favorable pressure gradients is described. Relaminarization is more likely to occur on the pressure side of a rotor blade. While stators also have strong favorable pressure gradients, the pressure surface is less likely to become turbulent at low to moderate Reynolds numbers. Accounting for the effects of relaminarization for blade heat transfer can substantially reduce the predicted rotor surface heat transfer. This in turn can lead to reduced rotor cooling requirements. Two dimensional midspan Navier-Stokes analyses were done for each of eighteen test cases using eleven different turbulence models. Results showed that including relaminarization effects generally improved the agreement with experimental data. The results of this work indicate that relatively small changes in rotor shape can be utilized to extend the likelihood of relaminarization to high Reynolds numbers. Predictions showing how rotor blade heat transfer at a high Reynolds number can be reduced through relaminarization are given.

Nomenclature

A^+	-	Near wall damping coefficient
b	-	Constant in equation for A^+
C_f	-	Friction factor
C_{LAG}	-	Constant in lag equation
C	-	True chord
C_x	-	Axial chord
D	-	Absolute heat transfer difference,%
h	-	Heat transfer coefficient
K	-	Acceleration parameter, $\mu(dU/ds)/(\rho U^2)$
M	-	Mach number
Nu	-	Nusselt number
n_{EXP}	-	Number of experimental data values
P	-	Pressure
$P+$	-	Pressure gradient, $\mu(dP/ds)/(\rho^2 U^3(C_f/2)^{3/2})$
Re	-	Reynolds number
s	-	Surface distance
s^+	-	Normalized surface distance, $s\rho U\sqrt{C_f/2}/\mu$
T	-	Temperature
Tu	-	Turbulence intensity
U	-	Freestream velocity
y	-	Normal distance to surface
β	-	Flow angle
γ	-	Intermittency
ρ	-	Density
θ	-	Momentum thickness
μ	-	Dynamic viscosity

Subscripts

C	-	Calculated
CRIT	-	Value at which relaminarization occurs
d	-	Leading edge diameter
EFF	-	Effective
EQ	-	Equilibrium value
EXP	-	Experimental
GAS	-	Molecular
LAM	-	Laminar
S	-	Surface distance from stagnation point
ST	-	Start of transition
T	-	Total surface distance
TURB	-	Turbulent
IN	-	Gas inlet
2	-	Blade row exit

INTRODUCTION

Gas turbine cycle efficiency is improved by increasing rotor inlet temperature and compressor pressure ratio. Higher pressure ratios result in higher coolant temperatures. The higher coolant and higher inlet temperatures make reducing blade heat transfer more significant. Designing blades so that the pressure surface boundary layer is mostly laminar may significantly reduce the average heat transfer for the entire blade. The pressure surface is likely to become turbulent due to an adverse pressure gradient close to the leading edge. If this is followed by a strong favorable pressure gradient, the boundary layer is likely to relaminarize. Calculations show that accounting for pressure surface relaminarization reduces overall blade heat load by approximately 20%, if the turbulence level is low. However, when the pressure surface is laminar, the heat transfer level is strongly influenced by the freestream turbulence level (Zhang and Han[1]). Consequently, at high freestream turbulence levels the heat transfer reduction may be less. To determine if relaminarization can be utilized to reduce blade heat transfer, accurate heat transfer predictions at high turbulence levels are needed.

Relaminarization is more likely to be a factor for rotor heat transfer than for stator heat transfer. Since the inlet relative total velocity is nearly twice that of the stator, the peak leading edge inviscid velocity is also twice as large for the rotor. The minimum inviscid pressure surface velocities are about the same for stators and rotors. Rotors have more diffusion, and are, therefore, more likely to transition. Relaminarization occurs in a strong favorable pressure gradient. Stators are less likely to relaminarize, since they are less likely to transition close to the leading edge. If the Reynolds number is sufficiently high, both stators and rotors are likely to transition close to the leading edge, but relaminarization is not likely to occur. Using relaminarization to reduce rotor pressure surface heat transfer was proposed by Brown and Martin[2]. Nicholson et al.[3] presented aerodynamic and heat transfer results for two rotor geometries. One was designed to relaminarize the pressure surface boundary layer. This blade shape had lower heat transfer, and no decrease in aerodynamic efficiency.

Relaminarization will only occur in high favorable pressure gradients. Favorable pressure gradients also delay the onset of transition. Unless the favorable pressure gradients are preceeded by an adverse pressure gradient, transition may not occur, especially at low to moderate Reynolds numbers. Calculations for a turbulent boundary layer give a laminar-like boundary layer, when the near wall damping coefficient is a function of the pressure gradient. Different functional forms have been proposed for the pressure gradient effect on the near wall damping coefficient. Cebeci and Smith[4] proposed one relationship, while Crawford and Kays[5] proposed another. Crawford and Kays[5], and Kays and Crawford[6] proposed that the local near wall damping not be a function of the local pressure gradient. They proposed that the coefficient be lagged to account for the time required to adjust the sublayer thickness to the pressure gradient change. The two references gave different lag equations. Nicholson et al.[3] and others maintain that a turbulent boundary will relaminarize when the acceleration parameter exceeds a value of approximately 3×10^{-6}. A significant computational difference between a relaminarized boundary layer, and one where the near wall damping coefficient is very large, is that the relaminarized boundary layer is laminar, while the other remains turbulent. All modeling which is a function of the intermittency would be different between the two approaches.

In summary, this work addresses the following questions: (1) Is a variable near wall damping coefficient appropriate, and if so, is the Cebeci-Smith model more appropriate than the Crawford and Kays model; (2) Should a lag equation be used to calculate either the pressure gradient parameter or the relaminarization parameter; (3) Should relaminarization be forced based on the pressure gradient, or should it be allowed to occur naturally through a variable near wall damping coefficient; and (4) Should the model to account for freestream turbulence effects be applied for turbulent boundary layers in the presence of strong favorable pressure gradients. These questions are addressed by comparisons with experimental heat transfer data from several sources, to determine which assumptions lead to the best agreement with data. Also, discussed in this work are comparisons with data using a $k-\omega$ turbulence model.

DESCRIPTION of ANALYSIS

Relaminarization can occur because the near wall damping coefficient, A^+, becomes very large, or it can be forced to occur based on the local value of the pressure gradient parameter, K. In all of the results presented, A^+ was taken as a function of the pressure gradient, P^+. Two similar forms of this relationship are given by Cebeci and Smith[4], and by Crawford and Kays[5].

$$A^+ = \frac{26}{1.0 + bP^+} \tag{1}$$

In the Cebeci-Smith model $b = 11.8$. In the Crawford and Kays model $b = 30.2$ for favorable pressure gradients, $P^+ < 0.0$, and $b = 26.1$ otherwise.

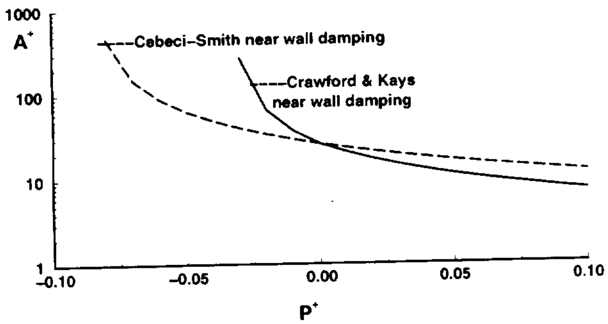


Fig. 1 Comparision of different near wall damping models.

Figure 1 compares the two approaches to calculating A^+. In the favorable pressure gradient region, where relaminarization is likely to occur, the Crawford and Kays model provides more near wall damping. In a negative pressure gradient the Crawford and Kays model gives a turbulent boundary layer that appears more laminar-like than the Cebeci-Smith model. If the Cebeci-Smith model gives better agreement with data, it is possible that a constant value for A^+ of 26 would give even better data agreement. If the Crawford and Kays model is preferable, a constant value for A^+ would not improve the agreement with data.

Crawford and Kays[5] also recommend that P^+ be replaced by an effective pressure gradient, $P^+_{\rm EFF}$. The value of $P^+_{\rm EFF}$ is calculated from:

$$\frac{dP^+_{\rm EFF}}{ds^+} = -(P^+_{\rm EFF} - P^+)/C_{\rm LAG} \qquad (2)$$

The recommended value for $C_{\rm LAG}$ was 4000.

An alternative approach to determining the lag in the near wall damping coefficient is given by Kays and Crawford[6] as:

$$\frac{dA^+_{\rm EFF}}{ds^+} = -(A^+_{\rm EFF} - A^+_{\rm EQ})/C_{\rm LAG} \qquad (3)$$

Here $A^+_{\rm EQ}$ is the value of A^+ determined from equation 1 using the equilibrium pressure gradient, P^+. The lag constant, $C_{\rm LAG}$, recommended value was again 4000.

If K is used as a criteria for relaminarization, it can also be lagged, so that:

$$\frac{dK_{\rm EFF}}{ds^+} = -(K_{\rm EFF} - K)/C_{\rm LAG} \qquad (4)$$

For comparison purposes, the same value of 4000 was used for $C_{\rm LAG}$ when calculating a lagged value for K.

Neglecting property variations, ds^+/ds is given by:

$$\frac{ds^+}{ds} = \frac{s^+}{s} + \frac{s^+}{U}\frac{dU}{ds} + \frac{s^+}{\sqrt{C_f/2}}\frac{d\sqrt{C_f/2}}{ds} \qquad (5)$$

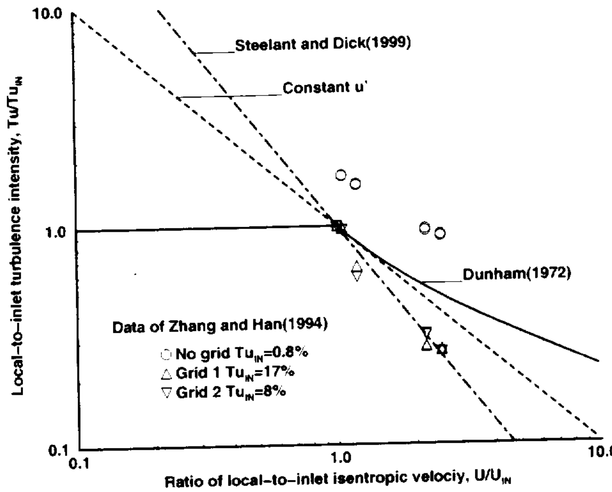


Fig. 2 Tu variation with velocity variation.

While ds is always positive, the right hand side could become negative in an adverse pressure gradient region. When ds^+/ds was negative, it was assumed that the effective value for the lagged parameter was the equilibrium value.

Mayle's[7] transition start criteria was used, where the Reynolds number at the start of transition is given by:

$$Re_{\theta-\rm ST} = 400 Tu^{-5/7} \qquad (6)$$

Mayle[7] recommended that a lower limit of 3% should be used for Tu when calculating $Re_{\theta-\rm ST}$. However, for the cases examined by Boyle and Simon[8], and for cases examined for this work, better agreement with data was found when the local Tu was allowed to decrease below 3%. The transition length model used was described by Boyle and Simon[8]. It is a modification of the model presented by Solomon et al.[9] to account for Mach number effects.

The local turbulent intensity is needed both to determine the start of transition, and to account for increased heat transfer due to freestream turbulence. Figure 2 illustrates approaches for determining the local freestream turbulence intensity, Tu, as a function of the local isentropic velocity. The correlation of Dunham[10] limits the freestream turbulence intensity to the upstream value when the local velocity is less than the upstream value. Another approach, used by Boyle and Simon[8], assumes that the turbulent fluctuations are constant so that:

$$Tu = Tu_{\rm IN} U_{\rm IN}/U \qquad (7)$$

Steelant and Dick[11] recommended that the local turbulence intensity be calculated from:

Table 1. Data comparisons.

Source	Label	β_{IN}	M_2	$Re_2 \times 10^{-6}$	Tu_{IN} %	T_W/T'_{IN}
Stator						
Arts et al. (1990)	ASR5	0°	0.93	0.59	6	0.75
	ASR1	0°	0.93	1.15	6	0.72
	ASR2	0°	0.92	2.14	6	0.73
Rotors						
Arts et al. (1998)	ARRE5	53°	1.1	0.54	4	0.71
	ARRE1	53°	1.1	1.06	4	0.71
	ARR16	53°	1.1	1.06	6	0.71
	ARRE2	53°	1.1	1.84	4	0.73
Giel et al. (1999)	G1RE5	64°	0.98	0.9	9	1.07
	G1RE1	64°	0.98	1.8	9	1.07
Giel et al. (2000)	G2RE5	61°	0.69	0.50	9	1.07
	G2RE1	61°	0.69	0.88	9	1.07
Blair (1994)	BDRE4	50°	0.14	0.12	6	1.07
	BDRE6	50°	0.10	0.56	6	1.07
	BORE2	36°	0.10	0.24	6	1.07
	BORE4	36°	0.06	0.42	6	1.07
Zhang and Han (1994)	ZHRE1	35°	0.02	0.10	14	1.07
	ZHRE2	35°	0.05	0.20	17	1.07
	ZHRE3	35°	0.07	0.30	17	1.07

$$Tu = Tu_{IN}(U_{IN}/U)^{3/2} \qquad (8)$$

Dunham's correlation shows the smallest variation in Tu, while the correlation of Steelant and Dick shows the largest variation. The data of Zhang and Han[1] show good agreement with the Steelant and Dick correlation for velocities greater than the upstream velocity. The local freestream velocity, U, was calculated from the local pressure ratio.

The transition models were incorporated into a quasi-3d Navier-Stokes analysis, (RVCQ3D). This code has been documented by Chima[12], and by Chima and Yokota[13]. C-type grids were generated using the method of Arnone et al.[14]. In this approach, the near-wall grid is embedded within a coarser grid obtained using the method of Sorenson[15]. For this work dense grids were used. A typical grid was 313×49 with 196 points on the blade surface. Calculations were for two dimensional flows, and comparisons were made for midspan heat transfer.

An algebraic turbulent eddy viscosity was used for most of the predictions. The one used is the model described by Chima et al.[16]. An algebraic model was used as a baseline for two reasons. First, it has been shown by Ameri and Arnone[17], and by Chima[18] that algebraic models of this type predict turbine blade surface heat transfer as accurately as two equation models. Second, the modifications to algebraic model to account for variable near wall damping, relaminarization, and freestream turbulence effects on laminar heat transfer are more straightforward. In addition, heat transfer distributions were calculated using the $k-\omega$ turbulence model described by Chima[18].

Because freestream turbulence was high for the cases examined, the Smith and Kuethe[19] model was used to account for the effects of freestream turbulence on the laminar flow. The augmented laminar viscosity is:

$$\mu_{LAM} = \mu_{GAS} + (1-\gamma)0.164\rho\, y\, Tu\, U \qquad (9)$$

where y is the normal distance from the blade, and μ_{GAS} is the molecular viscosity. This model is turned off for turbulent flow using the $1-\gamma$ term. It was generally found that augmenting the turbulence viscosity when the flow was fully turbulent resulted in poorer agreement with the experimental data. Data from Arts et al.[20] for a rotor at a Reynolds number of one million showed little increase in heat transfer on the rear of the pressure surface as the turbulence intensity increased. Calculations done with the Smith and Kuethe model applied even when the flow was turbulent overpredicted the effect of freestream turbulence for this case. Also, Blair[21] showed that freesteam turbulence effects on heat transfer are diminished for a turbulent boundary layer when the momentum thickness is small. The pressure surface momentum thickness is generally small. Since the Smith and Kuethe model does not account for turbulence scale effects, it is expected to only approximately account for turbulence effects. The effect of the Smith and Kuethe[19] model on the pretransition heat transfer will be discussed. The TuU product in the model is constant for most of the results presented. If Dunham's[10] correlation had been used, the TuU product would be less than the upstream value along the forward portion of the pressure surface, where the local velocity is less than the upstream velocity. If the correlation of Steelant and Dick[11] were used, the TuU product is greater than the upstream value in this region. Calculations using the Steelant and Dick variation showed leading edge region heat transfer much greater than both the experimental data and calculations done assuming the TuU product to be constant. The reason for the excessively high heat transfer is that the Smith and Kuethe[19] correlation was developed using the upstream values for Tu and U. Consequently, when the Steelant and Dick correlation was used, it was restricted to regions where the local velocity was greater than the upstream velocity. Where the velocity was less than the upstream velocity, the assumption was made

Table II. Description of model assumptions.

Label	Var. A^+	Lag	Tu Aug.	Tu Var.	Explicit Relaminarization	Relaminarization Lag
CKLPNTNR	CK	P^+	No	$TuU = C$	No	-
CSLPTANR	CS	P^+	Yes	$TuU = C$	No	-
CSNLTANR	CS	No	Yes	$TuU = C$	No	-
CKLPTANR	CK	P^+	Yes	$TuU = C$	No	-
CKNLTANR	CK	No	Yes	$TuU = C$	No	-
CKLATANR	CK	A^+	Yes	$TuU = C$	No	-
CKLPTARNL	CK	P^+	Yes	$TuU = C$	Yes	No
CKLPTARL	CK	P^+	Yes	$TuU = C$	Yes	Yes
CSLPTARNL	CS	P^+	Yes	$TuU = C$	Yes	No
CKLPSDRNL	CK	P^+	Yes	SD	Yes	No
$k-\omega$	-	-	-	-	-	-

that TuU was equal to the upstream value. Along the suction surface, the product would be greater than the upstream value.

Data Comparisons

Table I gives some characteristics of the experimental data used for comparisons. The stator data of Arts et al.[22] is included primarily for comparisons of modeling assumptions for freestream turbulence effects. The rotor geometry cases of Arts et al.[20] are for test cases of four and six percent inlet turbulence. The other rotor test cases are at these turbulence levels or higher. Dring et al.[23] gave the turbulence intensity between the stator and rotor of a large scale rotating turbine. Their measurements showed a total unsteadiness of 6.1 and 5.1 percent of the inlet relative velocity for tests with and without a turbulence grid installed in front of the upstream stator. The two test cases of Giel et al.[24,25] were for tests in a linear cascade with an aspect ratio less than one. The measured flows were highly three-dimensional, and the data showed significant suction surface spanwise heat transfer variations. Spanwise heat transfer variations on the pressure surface were small. The data are included because the work is concerned with identifying an appropriate approach to predicting heat transfer in favorable pressure gradients. Midspan heat transfer predictions using both two and three dimensional Navier-Stokes analysis will be compared with data for these low aspect ratio cases. All rotor data, except for those of Blair[26] at an inlet relative angle, β_{IN}, of 36°, are for design incidence. The data of Zhang and Han[1] are for very high freestream turbulence levels.

Table II summarizes the eleven models used to predict heat transfer. Models beginning with the label CK use the Crawford and Kays(CK) model for A^+ as a function of pressure gradient. Otherwise, the Cebeci-Smith model is used. The next two letters refer to lagging the near wall damping coefficient. If the letters are NL, there is no lagging, and if they are LA, A^+ is lagged explicitly. For the letters LP, it is the pressure gradient, P^+, which is lagged, and A^+ is calculated from the lagged value of P^+. The next two letters denotes whether the Smith and Kuethe augmentation model is used. Only one model, CKLPNTNR, omits the augmentation. If the letters are SD, the modified Steelant and Dick[11] variation in turbulence intensity is used both to augment the turbulence in the Smith and Kuethe model, and to determine the start of transition. If the next letter is N, there is no explicit relaminarization. For the four models with explicit relaminarization, only one, CKLPTARL, has a lagged relaminarization parameter, K. A significant difference between a case with explicit relaminarization, and one where A^+ becomes very large is that the intermittency, γ, reverts to zero for explicit relaminarization. With $\gamma = 0$, the Smith and Kuethe[19] augmentation model is used to augment the turbulent eddy viscosity.

Average surface values.

Tables III and IV show the average magnitude of the difference between the prediction and data for each of the model assumptions. Results are shown for just the pressure side(Table III), and for the entire blade, (Table IV). The values shown in the tables were calculated by:

$$D = 100 \sum_{n=1}^{n_{EXP}} |h_C - h_{EXP}| / n_{EXP} \overline{h_{EXP}} \qquad (10)$$

This estimate of the error is conservative because it does not allow for any positional uncertainty, or effective

Table III. Average model-to-experiment difference - Pressure side

	Average percentage difference										
	Model assumption										
Test case	CKLPNTNR	CSLPTANR	CSNLTANR	CKLPTANR	CKNLTANR	CKLATANR	CKLPTARNL	CKLPTARL	CSLPTARNL	CKLPSDRNL	$k-\omega$
ASR5	U 10	U 9	U 9	U 9	U 9	U 9	U 9	U 9	U 9	U 11	U 28
ASR1	U 43	O 12	O 9	O 9	O 10	U 10	U 10	U 10	U 10	U 16	O 28
ASR2	U 22	O 9	O 9	O 10	O 10	U 15	U 19	U 21	U 18	U 29	U 12
ARRE5	U 17	O 25	O 28	U 16	U 38	U 48	O 13	O 12	U 14	O 13	O 28
ARRE1	U 12	O 22	O 21	O 16	U 27	U 54	O 19	O 15	U 19	O 19	O 19
ARR16	U 11	O 20	O 22	U 16	U 29	U 58	O 25	O 26	O 25	O 24	O 15
ARRE2	U 10	O 20	O 21	O 16	O 20	U 56	O 22	O 21	U 22	O 23	O 14
G1RE5	U 59	U 35	U 36	U 17	U 56	U 59	U 13	U 12	U 13	U 16	U 34
G1RE1	U 58	U 45	U 45	U 54	U 55	U 71	U 27	U 26	U 27	U 30	U 12
G2RE5	U 20	O 16	U 20	O 12	U 29	U 31	O 22	O 22	O 20	O 20	U 24
G2RE1	U 31	U 19	U 25	U 27	U 50	U 55	O 29	O 21	O 30	O 31	U 20
BDRE1	U 49	O 14	O 15	O 14	O 14	O 12	O 13	O 15	O 13	O 14	U 27
BDRE6	U 48	O 19	O 20	O 19	O 20	O 17	O 18	O 24	U 18	O 18	U 27
BORE2	U 52	U 37	U 14	U 14	U 54	U 52	U 29	U 29	U 30	U 31	U 40
BORE4	U 54	U 35	U 41	U 45	U 52	U 53	U 27	U 30	U 27	U 28	U 39
ZHRE1	U 59	U 11	U 40	U 12	U 15	U 43	U 9	U 7	U 9	U 10	U 16
ZHRE2	U 66	U 54	U 44	U 52	U 52	U 52	O 18	O 16	U 17	O 12	U 15
ZHRE3	U 69	U 40	U 44	U 49	U 54	U 55	O 19	O 19	U 19	O 15	U 14
Average	U 40	U 26	U 27	U 27	U 34	U 42	19	18	19	U 20	U 29
Average	-39	-13	-15	-18	-25	-34	-4	1	-4	-5	-18

Table IV. Average model-to-experiment difference - Total blade

	Average percentage difference										
	Model assumption										
Test case	CKLPNTNR	CSLPTANR	CSNLTANR	CKLPTANR	CKNLTANR	CKLATANR	CKLPTARNL	CKLPTARL	CSLPTARNL	CKLPSDRNL	$k-\omega$
ASR5	U 33	U 14	U 14	U 14	U 14	U 13	U 14	U 14	U 14	U 17	O 54
ASR1	U 34	U 12	U 11	U 11	U 11	U 11	U 12	U 12	U 11	U 16	O 46
ASR2	U 24	O 11	O 11	U 12	U 12	U 14	U 15	U 16	U 15	U 32	O 34
ARRE5	U 23	O 34	O 35	O 29	U 41	U 46	O 27	O 27	U 28	O 25	O 55
ARRE1	U 13	O 26	O 26	O 22	O 27	U 39	O 23	O 20	O 25	O 19	O 33
ARR16	U 17	O 21	O 25	O 21	O 27	U 38	O 25	O 23	O 27	O 22	O 26
ARRE2	O 16	O 24	O 24	O 21	O 23	U 45	O 24	O 20	O 25	O 21	O 27
G1RE5	U 49	U 26	U 27	U 33	U 36	U 49	U 21	U 18	U 18	U 23	U 26
G1RE1	U 52	U 38	U 39	U 41	U 42	U 56	U 33	U 31	U 32	U 35	U 37
G2RE5	U 24	O 23	O 26	O 21	U 30	U 29	O 25	O 21	U 27	O 20	O 32
G2RE1	U 24	O 23	O 25	O 24	U 33	U 32	O 25	O 21	O 26	O 23	U 15
BDRE1	U 36	U 14	U 15	U 13	U 14	U 14	U 13	U 13	U 13	U 13	U 27
BDRE6	U 34	U 15	U 16	U 14	U 16	U 16	U 13	U 14	U 14	U 16	U 19
BORE2	U 41	U 26	U 30	U 28	U 33	U 40	U 21	U 20	U 21	U 22	U 37
BORE4	U 42	U 24	U 28	U 29	U 34	U 38	U 19	U 21	U 20	U 20	U 38
ZHRE1	U 49	U 26	U 25	U 26	U 27	U 32	U 14	U 13	U 14	U 15	U 36
ZHRE2	U 52	U 31	U 29	U 31	U 31	U 40	O 19	O 17	O 19	O 14	U 31
ZHRE3	U 50	U 27	U 29	U 30	U 31	U 31	O 20	O 17	O 20	U 15	U 28
Average	U 34	U 23	U 24	U 23	U 27	U 32	U 20	U 19	U 21	U 21	U 33
Average	-31	-5	-7	-8	-11	-20	-1	-1	-1	-8	0

width of the measurements. In regions of high gradients the actual error would be less if the measurement locations were moved within their uncertainty limits.

For Table III, $\overline{h}_{EXP}$ is the average experimental heat transfer coefficient for just the pressure surface. For the results in Table IV, this value is the average for the entire blade. The letters U and O in these tables indicate whether the average predicted heat transfer was either less,(U), or greater,(O), than the experimental value. Generally, the magnitude of the average difference was less than that shown in Tables III and IV. Only if the model either underpredicted or overpredicted the heat transfer at every measurement location would the average difference and the value of D be the same. Two overall averages are shown for each model. The one preceeded by a U or O is the average absolute difference, D, of the eighteen cases. The letter is U if more than half the cases were underpredicted, and O if more than half are overpredicted. The other one is the average of all data points for all eighteen cases, without taking the absolute value. A negative value means that the analysis underpredicted the heat transfer.

Comparing results using the CKLPNTNR model with those using the CKLPTANR model shows the effect of the Smith and Kuethe turbulent augmentation model. On the pressure side, not augmenting the eddy viscosity resulted in an underprediction for all cases. The average absolute difference was 40%. The average undeprediction was nearly as large, 39%. Seven of the eighteen pressure surface cases were overpredicted using the CKLPTANR model, and overall the underprediction was 18%. Considering the entire surface, Table IV shows that the CKLPNTNR model gives an overprediction for only one of the eighteen cases. Again, the absolute difference is large, 34%, and the underprediction is nearly as great, 31%. The CKLPTANR model gives an overprediction for six cases, and the underprediction is 18%. This shows the desirability of including a model for the effect of freestream turbulence on eddy viscosity, and the reasonableness of the model chosen.

Table III shows that the Crawford and Kays model with a lag for P^+, CKLPTANR, has an average absolute difference of 27%. Without a lag for P^+, CKNLTANR, the average absolute difference increases to 34%. As figure 1 shows, the effect of a lagging P^+ is smaller for the Cebeci-Smith model. Both the CSLPTANR and CSNLTANR results show similar average absolute differences. For both the pressure surface, and the entire blade, the CKLPTANR and CSLPTANR models have similar, but not identical, absolute differences. The CKLPTANR model is more sensitive to P^+ variation, and underpredicts the heat transfer to a greater extent. Based on the comparisons between the CSLPTANR and CKLPTANR model results, there is little reason to believe that a constant value for A^+ would not give satisfactory heat transfer predictions. However, since a value for A^+ as a function of P^+_{EFF} agrees better with data than A^+ as a function of P^+, using a non-constant value for A^+ is appropriate.

A constant A^+ is not affected by whether P^+ is lagged or not. The CKLATANR model, where A^+ is lagged, but the equilibrium value of A^+ is calculated from the local value of P^+ has a greater absolute difference than the CKLPTANR model, indicating that A^+ should not be lagged directly.

The CKLPTARNL and CKLPTARL model results show that forcing relaminarization explicitly improves the agreement with data. Comparing these model results with the CKLPTANR results show that explicit relaminarization improves the average agreement with data. The improvement in the average absolute difference is nearly 10% for the pressure side, and over 3% for the total blade. The improvement in the average difference is greater, being nearly 17% for the pressure side, and 7% for the total blade. These results indicate that explicit relaminarization is appropriate. With explicit relaminarization freestream turbulence increases heat transfer whenever the boundary layer is not fully turbulent. Whether K or K_{EFF} should be used as a criteria for relaminarization is addressed subsequently.

The differences in predicted heat transfer between the CKLPTARNL and CSLPTARNL models are less than the differences between the CKLPTANR and CSLPTANR models. The near wall damping models are employed only when the the flow is not laminar. For the assumption of relaminarization, there is little evidence to prefer one form of near wall damping over the other.

The modified Steelant and Dick model for the local turbulence intensity did not improve heat transfer predictions compared with the CKLPTARNL model. The model predicted the variation in turbulence intensity for the data of Zhang and Han[1]. But, it resulted in decreased augmentation in the Smith and Kuethe model for the rear portion of the pressure surface.

It will be shown that when the $k-\omega$ model underpredicted heat transfer, it was often due to not accounting for freestream turbulence effects prior to transition. When heat transfer was overpredicted, it was often due to transition occurring sooner than was seen in the data.

Blade surface comparisons.

Next, heat transfer comparisons will be shown for each of the eighteen cases to illustrate the local heat transfer for the different model assumptions. Eleven of the cases show the CKLPTARNL model results. For clarity, each comparison with data shows results for only a few model assumptions.

Stator vane comparisons. Figure 3 shows comparisons with the stator data of Arts et al.[22]. The lowest Reynolds number results show that augmenting laminar viscosity to account for freestream turbulence improves the agreement with data, both in the leading edge region and all along the pressure surface. The $k-\omega$ model shows too early transition on both pressure and suction surfaces. It also shows no augmentation of laminar heat transfer due to high freestream turbulence.

At the intermediate Reynolds number both Crawford and Kays near wall damping models agree well with the data. The Cebeci-Smith model gives too high heat transfer towards the rear of the pressure surface. The explicit relaminarization model, CKLPTARNL, gives lower heat transfer for the rear of the pressure surface, indicating that a relaminarization criteria greater than 3×10^{-6} is appropriate. At the highest Reynolds number, the pressure surface heat transfer is significantly underpredicted by the CKLPTARNL model, and even more so by the CKLPSDRNL model. The data show no evidence of relaminarization. Because of favorable

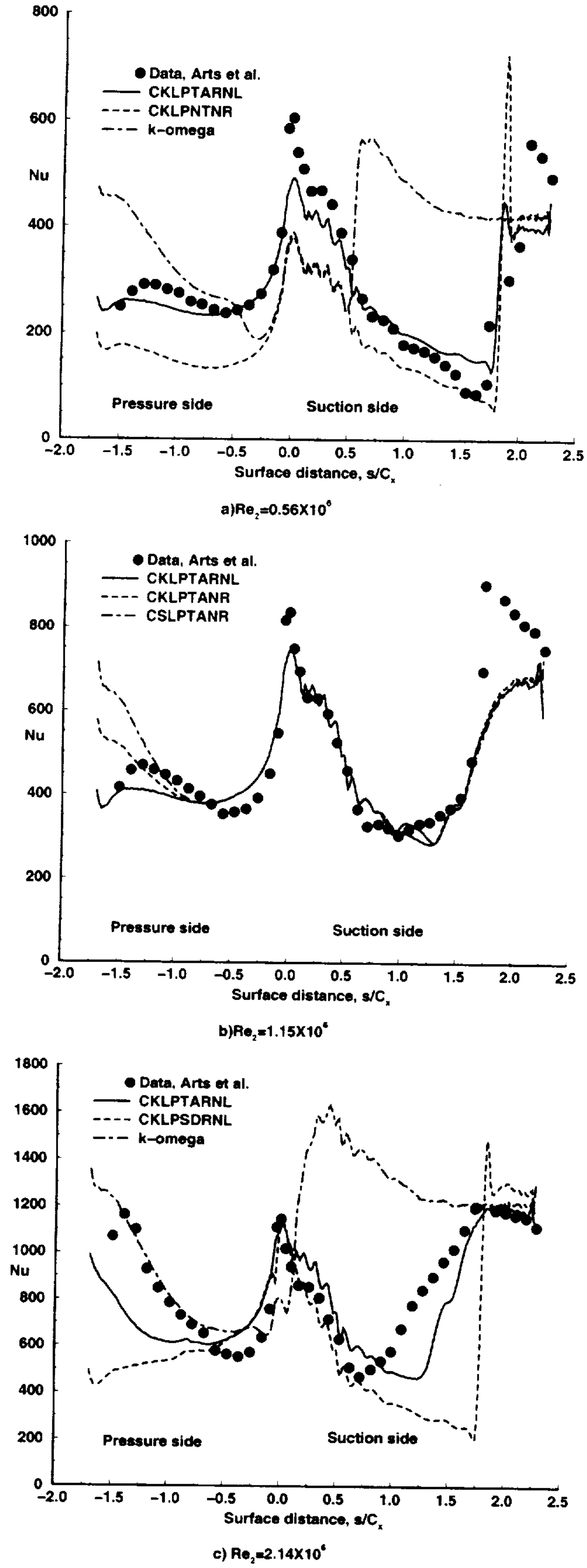


Fig. 3 Comparison with the data of Arts et al.(1990)

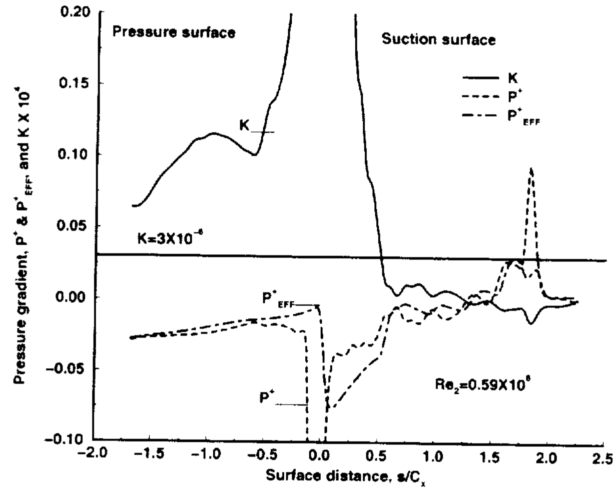
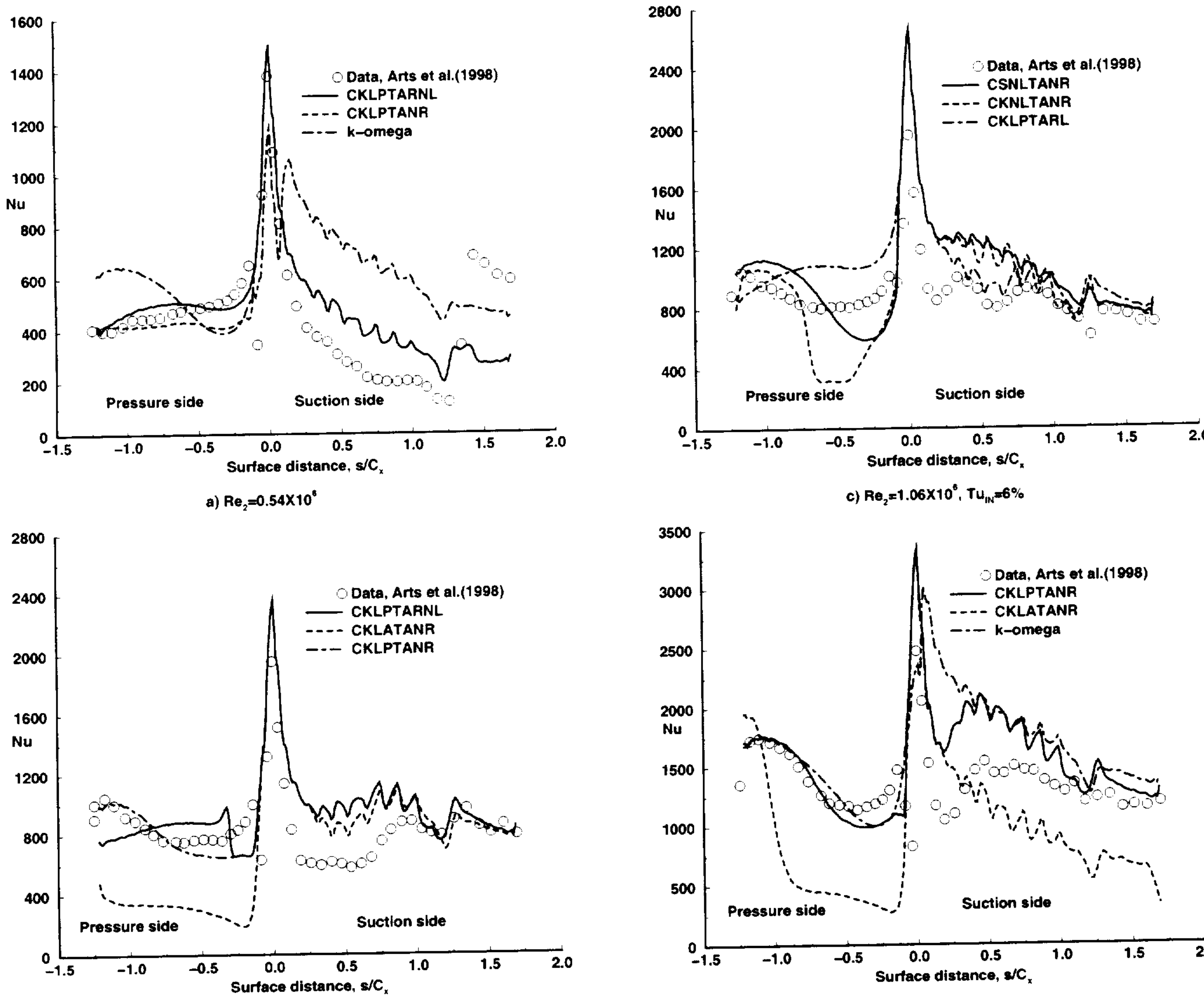


Fig. 4 Pressure gradient parameters for stator of Arts et al.(1990)

pressure gradients, the pressure surface was predicted to be in transitional flow at this Reynolds number, even without explicit relaminarization. The $k-\omega$ model predicts pressure surface heat transfer well. But, the suction surface heat transfer is overpredicted due to early transition.

Figure 4 shows that the local K value exceeded 3×10^{-6} for a Reynolds number of 0.59×10^6. The highest Reynolds number of 2.14×10^6 show a K distribution similar in shape, but only approximately one fourth as great. For the high Reynolds number case, explicit relaminarization only moved the start of transition somewhat further back on the pressure surface, since K was below the critical value for the much of the surface distance. Figure 4 shows that, over much of the vane pressure surface, there is little difference between P^+ and $P^+_{\rm EFF}$.

Rotor blade comparisons. Figure 5 compares measured and predicted heat transfer for the rotor of Arts et al.[20]. At the lowest Reynolds number the CKLPTARNL model agrees well with the data for the pressure surface. Here, relaminarization based on K is appropriate. Table III gives absolute differences of U 16 and O 13 for the CKLPTANR and CKLPTARNL models respectively. However, figure 5a shows good agreement with the experimental pressure surface data. For this case, the CKLPTANR model underpredicted the pressure surface data by 3%, while the CKLPTARNL model overpredicted the pressure surface data by 6%. Differences in the high gradient region near the leading edge accounted for the higher values in Table III. This illustrates the conservative nature of the approach taken to calculate the values in Tables III and IV.



a) Re_2=0.54X10^6

b) Re_2=1.06X10^6, Tu_{IN}=4%

c) Re_2=1.06X10^6, Tu_{IN}=6%

d) Re_2=1.84X10^6

Fig. 5 Heat transfer comparisons for rotor of Arts et al.(1998).

The CKLPTARNL and CKLPTARL results in Table III shows that lagging K has little effect on the pressure surface prediction for the low Reynolds number case. Both the $k-\omega$ and CKLPNTNR model typically give leading edge Frossling numbers near one. With high freestream turbulence, data show Frossling numbers typically forty to fifty percent greater. Suction surface transition occurs close to the trailing edge because of the favorable pressure gradients. The Smith and Kuethe freestream turbulence model overpredicts laminar region suction surface heat transfer.

Figure 5b shows good agreement with the pressure surface data for the CKLPTANR model. The relaminarization model, CKLATARNL, shows a flat pressure surface heat transfer distribution, and underpredicts the data for the last thirty percent of the surface distance. This implies that a higher value of K_{CRIT} would be appropriate for the relaminarization criteria. On the suction surface, the CKLPTARNL model gives slightly higher heat transfer than the CKLPTANR model. Both,however, overpredict the heat transfer for much of the suction surface.

For the higher turbulence intensity comparisons in figure 15c, the relaminarization model, CKLPTARL, predicts the shape of the pressure surface heat transfer, but gives the heat transfer level is too high. Improvements in the laminar augmentation model would improve the agreement with data. This model also gives good agreement with the suction surface heat transfer.

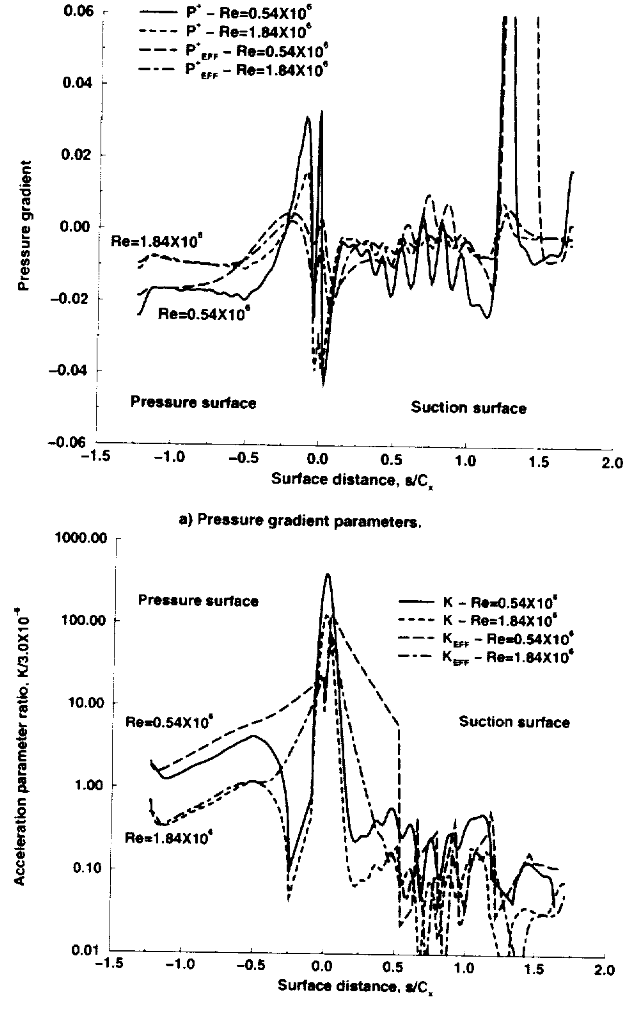
Without relaminarization, the Cebeci-Smith near wall damping model shows better agreement with the data.

The highest Reynolds number comparisons show that the CKLPTANR and $k-\omega$ models give good agreement with data for the pressure surface. On the suction surface both models overpredict the heat transfer. For the CKLPTANR model this is due to overpredicting the effect of freestream turbulence prior to transition. Figures 15b and 15d show that the CKLATANR model gives poor agreement with pressure surface data. This occurred because the value of $A^+_{\rm EFF}$ was much greater than the local value of A^+.

Figures 5 shows that the analysis overpredicts freestream turbulence effects prior to transition for the suction surface. This is a consequence of how the Smith and Kuethe[19] model was implemented. The turbulent eddy viscosity was augmented for a large number of grid lines extending outward from the surface. Boyle and Simon[8] implemented the Smith and Kuethe model differently, and achieved better agreement with data. They added the augmentation only in the inner region of the boundary layer. However, the inner region was determined from calculations for a turbulent boundary layer. Also, the location, in terms of y^+, varied depending on the type of turbulence model used. This indicates that the Smith and Kuethe augmentation should be applied only over a range of y^+ values. Unfortunately, the appropriate y^+ value is not known.

Figure 6a shows the variation in P^+ and $P^+_{\rm EFF}$ along the blade surface for the lowest and highest Reynolds numbers. At the highest Reynolds number, there is little difference between the lagged and local values of P^+. At the lowest Reynolds numbers the differences are more noticeable, and are caused by the high value of P^+ near stagnation. At the lowest Reynolds number the maximum value of s^+ on the pressure side is only about ten times the value of $C_{\rm LAG}$. At the highest Reynolds number, the maximum value for s^+ is over thirty times the value of $C_{\rm LAG}$.

Comparing figures 6a and 6b shows that the ratio of the maximum-to-average value of K is much greater than the same ratio for P^+. For clarity, the ratio of K to the value used to set relaminarization, 3×10^{-6}, is shown, and negative K values were omitted. In the relaminarization model, when the ratio exceeds one, relaminarization occurs. This illustrates why lagging K to determine $K_{\rm EFF}$ is not appropriate. In the stagnation region the freestream velocity approaches zero, and the local value of K becomes very large. At the lower



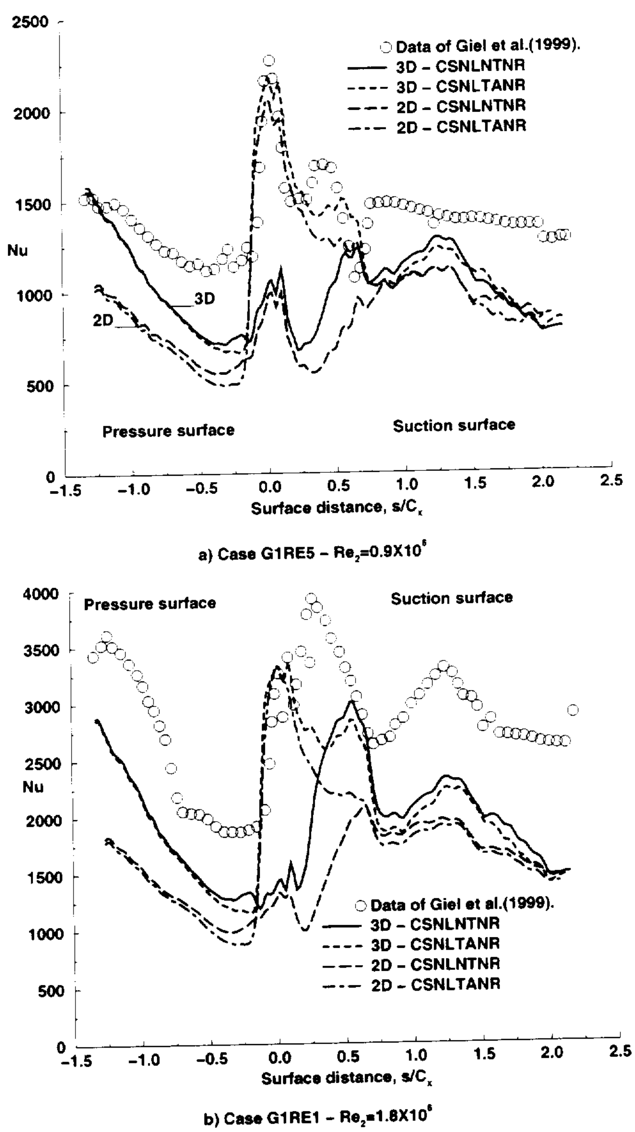
a) Pressure gradient parameters.

b) Acceleration parameters.

Fig. 6 Presure gradient parameters for rotor of Arts et al.(1997).

Reynolds number, the high K value near the stagnation point causes $K_{\rm EFF}$ to exceed K all along the blade pressure surface. The is because the lag coefficient, $C_{\rm LAG}$, is about ten percent of the trailing edge s^+ value. At the higher Reynolds number the local s^+ value is nearly four times greater, and $K_{\rm EFF}$ approaches K.

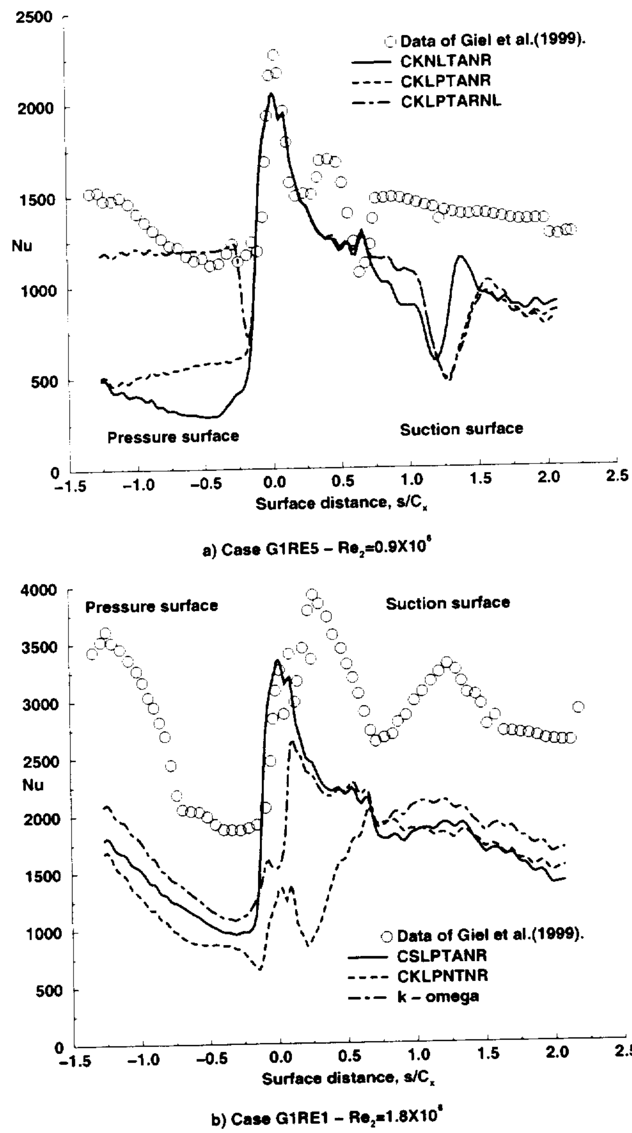
The suction surface results in figure 6 illustrate that, if a lag equation is implemented, it should be calculated from a slightly smoothed parameter value. Too much smoothing will introduce additional lagging. In Navier-Stokes, as opposed to boundary layer, calculations large streamwise steps are used. For a hundred surface points the distance between grid lines, Δs^+ is on the order of ten percent of the lag constant. This can introduce instabilities in calculating the lagged value if the local value is oscillating.



a) Case G1RE5 - Re$_2$=0.9X10^6

b) Case G1RE1 - Re$_2$=1.8X10^6

Fig. 7 - Comparison of 2D and 3D midspan predictions.



a) Case G1RE5 - Re$_2$=0.9X10^6

b) Case G1RE1 - Re$_2$=1.8X10^6

Fig. 8 Two dimensional heat transfer predictions and data.

Both two-dimensional(2D) and three-dimensional(3D) flow analyses were done for the low aspect ratio test cases of Giel et al.[24,25]. Figure 7 compares midspan heat transfer from the two Navier-Stokes analyses. The 3D analysis was done with and without augmentation for freestream turbulence. The turbulent eddy viscosity was calculated using the model of Chima et al.[16]. The 3D analysis was described by Chima and Yokota[13] and Chima[27]. The 3D predictions with augmentation for freestream turbulence were for the CSNLTANR turbulence model. Calculations done without freestream turbulence augmentation are labeled CSNLNTNR. The experimental data of Giel et al.[24] showed large spanwise suction surface heat transfer variations, and these variations were also seen in the 3D predictions. However, at midspan the only significant difference between the 2D and 3D suction surface heat transfer predictions is that the 3D prediction shows an earlier transition location. The difference between the 2D and 3D pressure surface heat transfer predictions was unexpected. Data and the 3D prediction showed little spanwise variation. However, beyond the leading edge region the 2D predictions are lower than the 3D prediction. For the pressure surface as a whole, the 2D predictions are 15% lower than the 3D predictions. Accounting for three dimensional effects would increase the predicted heat transfer for these two cases. The CSNLTANR model would change from U 36 and U 45 to U 21 and U 29 using the 3D midspan predictions.

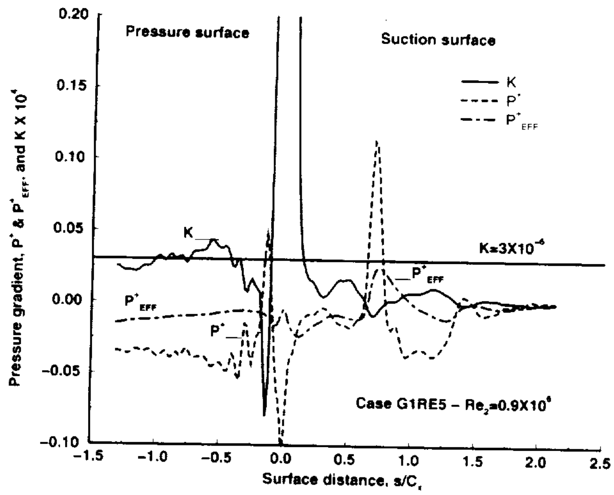
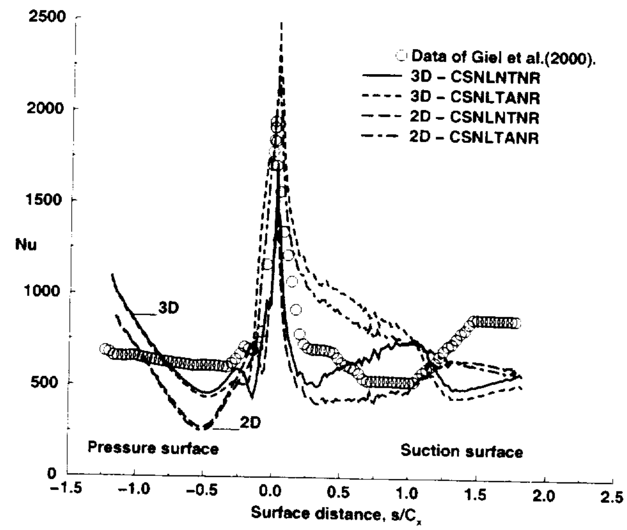


Fig. 9 Pressure gradient parameters for rotor of Giel et al.(1999).

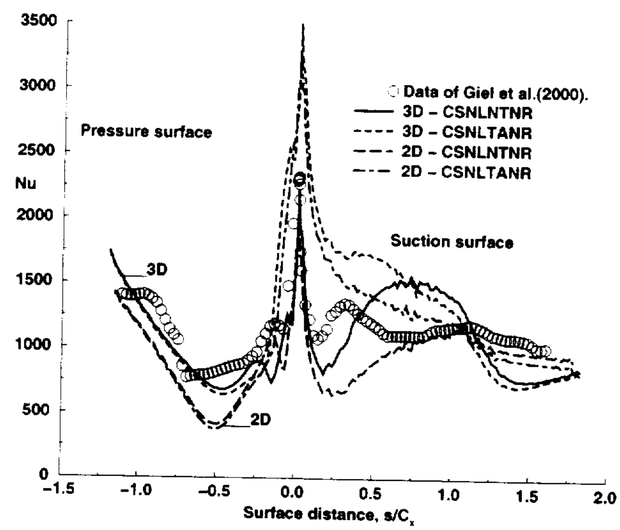
Figure 8 shows 2D heat transfer comparisons for the rotor tested by Giel et al.[24]. For the lower Reynolds number comparison only the CKLPTARNL model approaches the pressure surface heat transfer. In the CKLPTANR model relaminarization does not occur. Because of strong favorable pressure gradients, A^+ remains very large, and the pressure surface heat transfer remains low. In the CKLPTARNL model relaminarization occurs. With relaminarization the Smith and Kuethe model is activated. The suction surface is underpredicted, but as figure 7a shows, the Cebeci-Smith models are closer to the data. The noticeable differences between the CKLPTANR and CKNLTANR model results are due to lagging the pressure gradient. The CKLPNTNR model results in figure 8b show that neglecting freestream turbulence effects gives heat transfer much lower than the data. Figure 8b shows that the CSLPTANR model results are closer to the pressure surface data, than are the CKLPTANR model results. The CSLPTANR model predicts lower pressure surface A^+ values.

Figure 9 shows the acceleration and pressure gradient parameters for the low Reynolds number, G1RE5, case. The acceleration parameter, K, exceeds 3×10^{-6} on the pressure surface. But, the data in figure 8a does not show a flat pressure surface heat transfer distribution, characteristic of relaminarized flow. This again implies a relaminarization criteria greater than 3×10^{-6}. Over much of the pressure surface $P^+_{\rm EFF}$ is only about half of the value of the local pressure gradient, P^+.

Figures 10-12 show comparisons with data for tests done in the same facility as for comparisons shown in figures 7-9, but for a different rotor geometry. The Reynolds numbers were also different. The comparison of 2D and 3D midspan heat transfer shown in figure



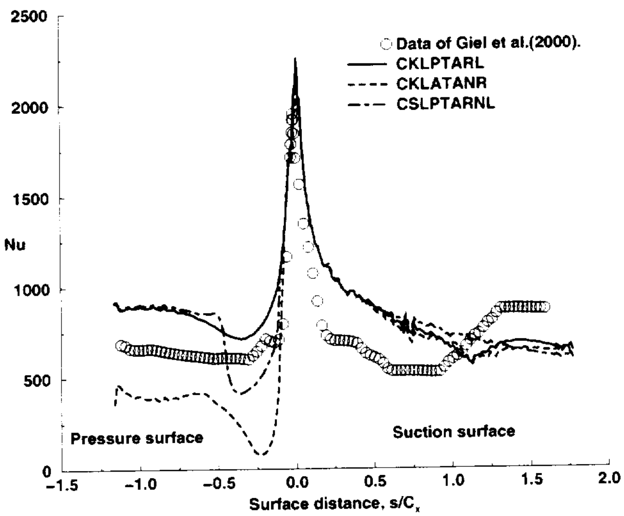
a) Case G2RE5 – Re2=0.50X10^6



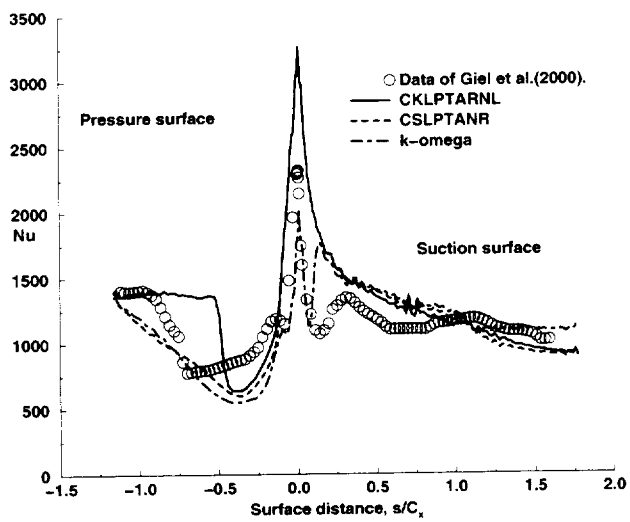
b) Case G2RE1 – Re2=0.88X10^6

Fig. 10 Comparison of 2D and 3D midspan heat transfer.

10 is similar to that shown in figure 7. On the suction surface the model without augmentation, CSNLNTNR, shows an earlier transition start for 3D flow than it does for 2D flow. The results in Table III for the CSNLTANR model would change from U 20 and U 25 to O 20 and U 19 if the 2D predictions were replaced by the 3D predictions. The change in sign from U 20 to O 20 is misleading. The average pressure surface heat transfer goes from a 10% underprediction to a 6% overprediction. These two cases also have 2D pressure surface 15% lower than the 3D predictions for the same turbulence model. Fourteen of the eighteen test cases were for blades with a greater aspect ratio. The differences between 2D and 3D predictions would be less than for these two cases.



a) Case G2RE5 – Re_2=0.50X10^6



b) Case G2RE1 – Re_2=0.88X10^6

Fig. 11 Comparison of heat transfer model predictions with data.

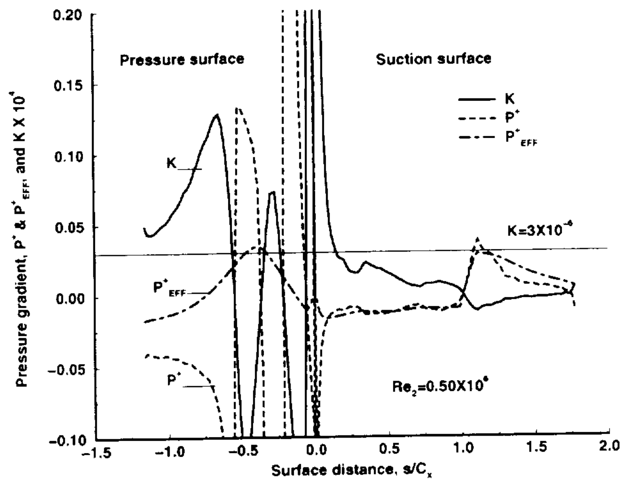


Fig. 12 Pressure gradient parameters for rotor G2RE5.

Accounting for 3D predictions for the four cases of Giel et al.[24,25] would change the overall pressure side CSNLTANR model averages from U 27% and -15% to U 24% and -12%. Additional calculations for these four cases using relaminarization models showed differences between 2D and 3D midspan heat transfer about half that for the non-relaminarizing models.

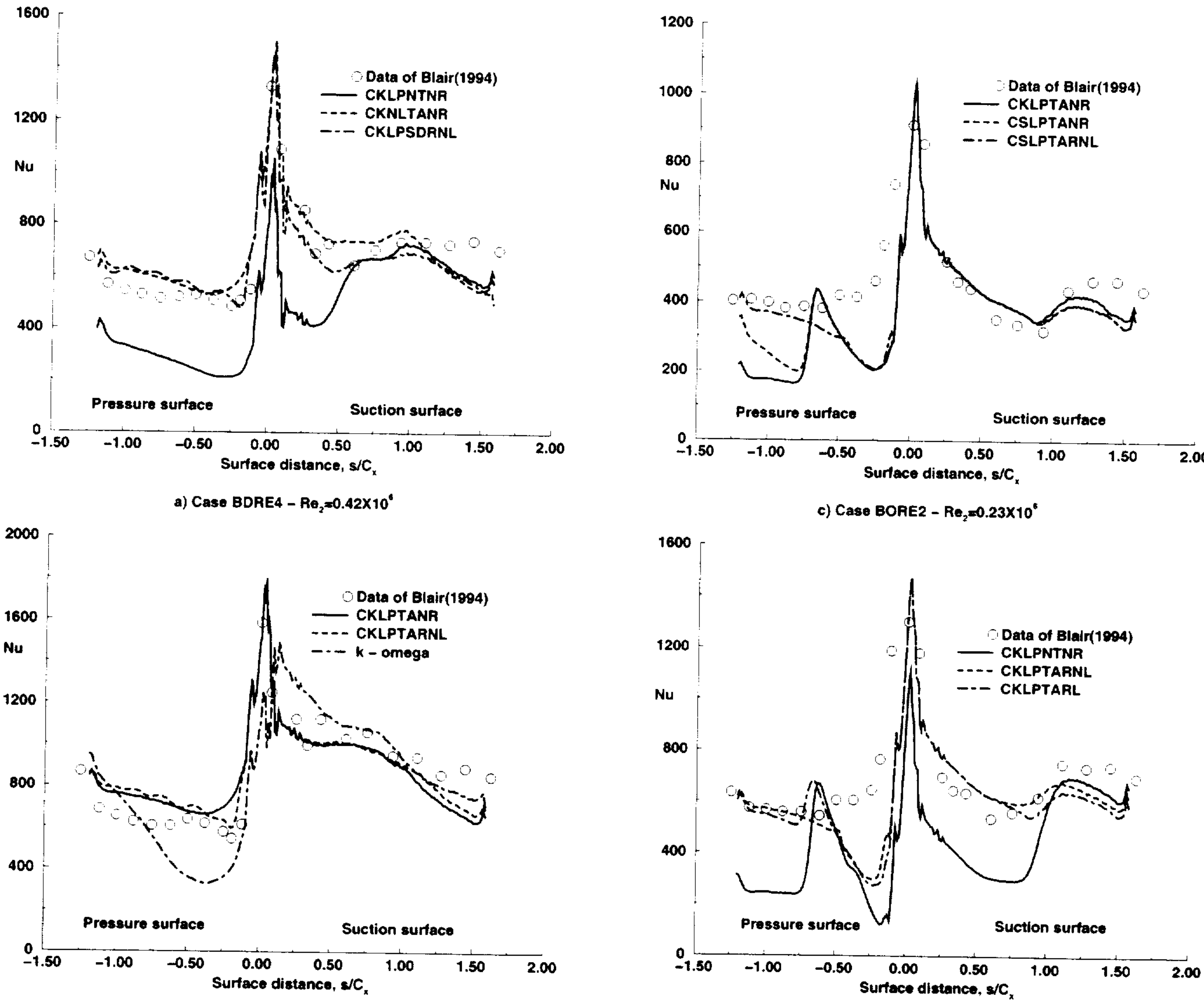
Figure 11a shows that the CKLATANR model, which lags A^+ directly, underpredicts the pressure surface heat transfer. This is consistent with the comparisons shown in figure 5b. Table III shows that the Crawford and Kays model and the Cebeci-Smith model go from underpredicting the heat transfer to overpredicting it when a lag equation is used for P^+ for this test case. The CKLPTANR model is in reasonable agreement with the stagnation region heat transfer, but significantly overpredicts the suction surface heat transfer prior to transition. The CSLPTARNL model results are similar to those for the CKLPTARL model. With no relaminarization lag, heat transfer is underpredicted on the forward part of the pressure surface.

For the higher Reynolds number case shown in figure 11b, the $k-\omega$ and CSLPTANR models agree well with the pressure surface data. The $k-\omega$ and CKLPTANR model results are very close over most of the suction surface, and the flow is predicted to be turbulent. The heat transfer overprediction after transition is not due to overestimating freestream turbulence effects. It is possibly due to three-dimensional effects.

Figure 12 shows large variations in pressure surface pressure gradient and acceleration parameters at the lower Reynolds number of 0.50×10^6. The pressure surface flow accelerates, decelerates, and then reaccelerates. This accounts for the large difference between P^+ and $P^+_{\rm EFF}$, even close to the trailing edge.

Figures 13a and 13b show comparisons with the data of Blair[26] for design incidence. For theses case lagging P^+ shows little effect. The CKNLTANR model agrees well with the data in figure 13a, and the CKLPTANR model agrees reasonably well with the data in figure 13b. Figure 13b shows almost the same heat transfer rates when K is lagged and when it is not. The $k-\omega$ model does not agree well with the pressure surface data, but does agree well for the suction surface.

Figures 13c and 13d show that off-design incidence cases have poorer agreement than design incidence cases. There is good agreement with the suction surface data. The relaminarizing models agree well with data for the aft half of the pressure surface, but all models underpredict heat transfer for the forward portion.



a) Case BDRE4 – Re_2=0.42X10^6

b) Case BDRE6 – Re_2=0.56X10^6

c) Case BORE2 – Re_2=0.23X10^6

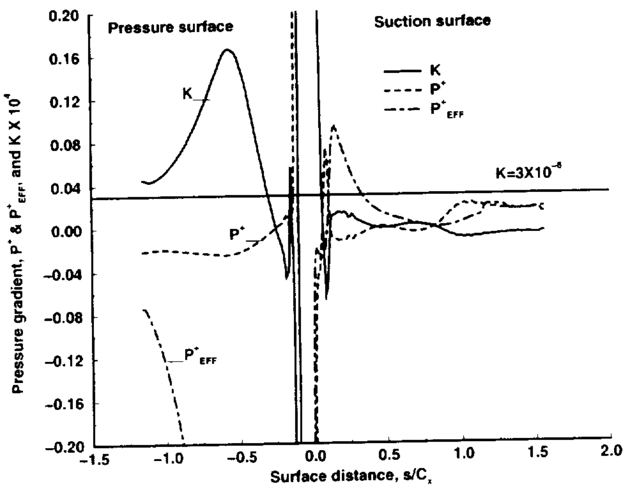
d) Case BORE4 – Re_2=0.42X10^6

Fig. 13 Heat transfer comparisons for data of Blair(1994).

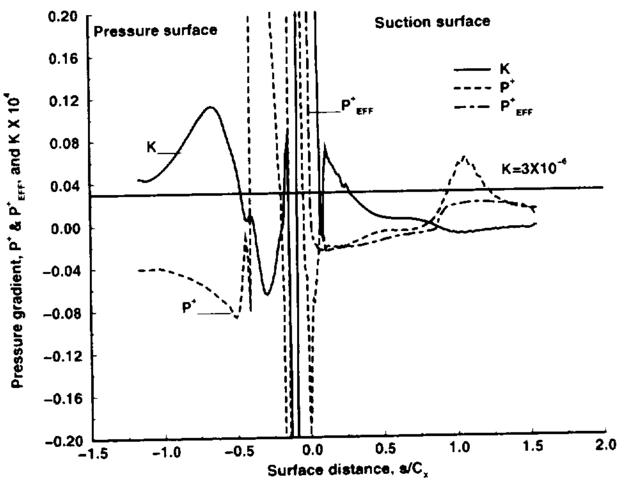
The pressure gradient parameters in figure 14 are for a Reynolds number lower than in the previous cases. The design incidence curves in figure 14a and those in figure 12 have similar shapes. P^+ and P^+_{EFF} differ substantially, even near the pressure surface trailing edge. At off-design incidence the flows accelerate, decelerate, and finally accelerate along the pressure surface. The effective pressure gradient, P^+_{EFF}, on the pressure surface is so dependent on what happens near the leading edge, that it is positive and off the scale in figure 14b. This behavior, resulting from the low Reynolds number, and the associated low s^+ values, makes any use of a lag equation problematic.

Figure 15 shows comparisons with the data for the three low Reynolds number cases of Zhang and Han[1] The cases have high inlet turbulence. For the lowest Reynolds number both the CKLPTARNL and CKLPSDRNL models agree well with the pressure surface data. Because the TuL product is lower with the Steelant and Dick freestream turbulence intensity model, the CKLPSDRNL model results are lower than those with the CKLPTARNL model. The CKLPSDRNL model predicts suction surface heat transfer better. The CKLPNTNR model results show that, not accounting for freestream turbulence severely underpredicts the surface heat transfer.

Figure 15b shows data comparisons with data for three Cebeci-Smith near wall damping models. Only the CSLPTARNL relaminarization model shows the same shape of pressure surface heat transfer as the data.



a) Case BDRE42 – Design incidence

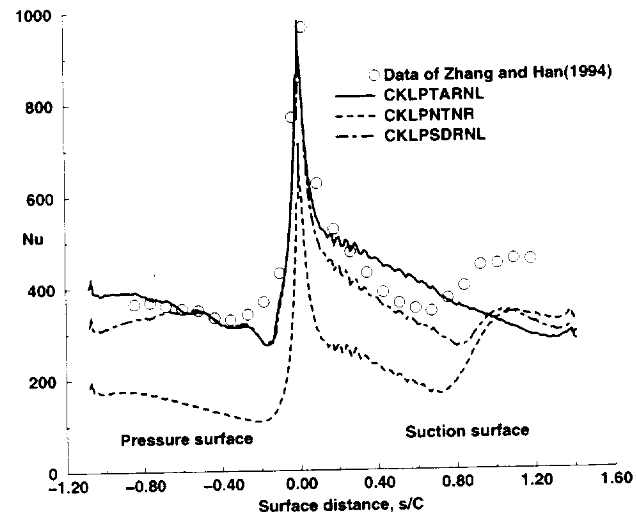


b) Case BORE2 – Off design incidence.

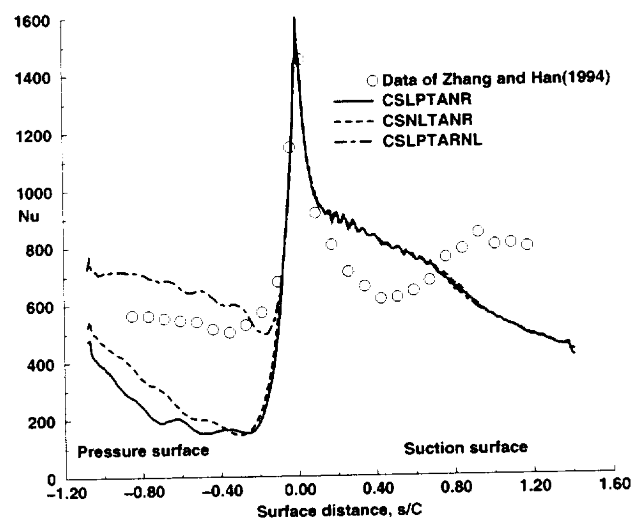
Fig. 14 Pressure gradient parameters for rotor of Blair(1994) at Re=0.42X10^6

The non-relaminarizing models have very low pressure surface heat transfer after the leading edge. The apparent transition seen in the suction surface data is not seen in the predictions.

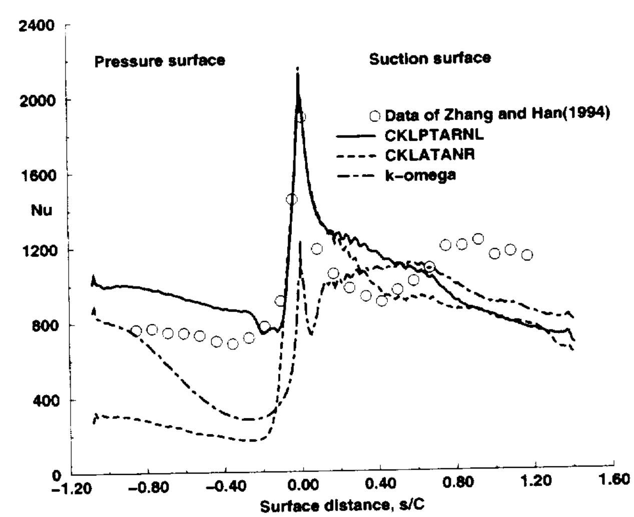
Figure 15c, for the highest Reynolds number, again shows that a relaminarization model best predicts the shape of the pressure surface heat transfer distribution. Without relaminarization, and, therefore, without augmentation due to freestream turbulence after transition, the heat transfer is low due to strong near wall damping at this still relatively low Reynolds number. On the pressure surface, the $k-\omega$ model shows very low heat transfer just after the leading edge region. This model also underpredicts the leading edge region heat transfer. All three model predict similar suction surface heat transfer away from the leading edge region.



a) Case ZHRE1 – Re$_2$=0.10X10^6



b) Case ZHRE2 – Re$_2$=0.20X10^6



c) Case ZHRE3 – Re$_2$=0.30X10^6

Fig. 15 Heat transfer comparisons for rotor of Zhang and Han.

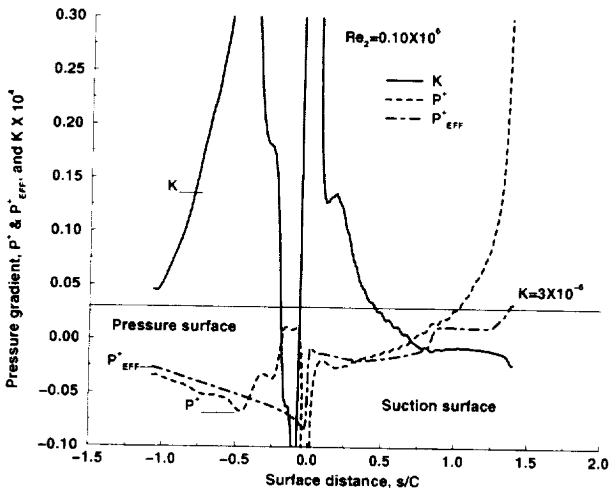


Fig. 16 Pressure gradient parameters for rotor of Zhang and Han(1994).

Figure 16 shows the acceleration parameters for the rotor of Zhang and Han[1] at the lowest Reynolds number. The values of K are very large. Even if divided by three to account for the highest Reynolds number, relaminarization is indicated. Over much of the pressure surface there is little difference between the local and lagged pressure gradient values.

CONCLUSIONS and RECOMMENDATIONS

Based on the results for the entire blade a variable near wall damping coefficient is appropriate. The Crawford and Kays[5] damping coefficient produces a laminar like boundary layer at a lower favorable pressure gradient than does the Cebeci-Smith damping coefficient. The Crawford and Kays model was more likely to underpredict the heat transfer. The results of this work indicate that a constant value of $A^+ = 26$ would overpredict the heat transfer level for many cases.

Explicit relaminarization improved agreement with data, particularly at low Reynolds numbers. The improvement occurred because when relaminarization occurred, the Smith and Kuethe[19] turbulence model was used to increase eddy viscosity. The average heat transfer increased when relaminarization occurred. For the forward portion of the pressure surface, predictions with a relaminarized model and data gave heat transfer rates exceeding fully turbulent values for some cases.

The lag equation for P^+ gave reasonable agreement with data. A lag equation for either A^+ or K was susceptible to giving physically unrealistic results, due to the extreme variability of these quantities near the stagnation point.

Neglecting freestream turbulence effects on laminar heat transfer always underpredicted the pressure surface heat transfer. The $k-\omega$ model, described by Chima[18], predicted leading edge Frossling numbers near one. The effects of freestream turbulence on leading edge heat transfer were not seen with the $k-\omega$ model. Consequently, this model on average underpredicted pressure side heat transfer. But for some cases this model overpredicted the heat transfer. Where the model overpredicted the heat transfer it was caused by transition occurring closer to the leading edge than was seen in the data. The $k-\omega$ model agreed better with data at high Reynolds numbers.

The models presented here can easily be incorporated into a a three-dimensional Navier-Stokes code. These results show that if K is maintained at a level of approximately 4×10^{-6}, the pressure surface is likely to be laminar. Pressure surfaces that appeared laminar were seen for exit Reynolds numbers approaching one million. Rotor Reynolds numbers in this range are representative of those in the high pressure turbine. The benefits of designing blades with pressure surface relaminarization are dependent on the local turbulence level. Methods for predicting the effects of both turbulence level and scale on heat transfer are needed to be able to reliably quantify the benefits of relaminarization.

The Smith and Kuethe[19] model for accounting for the effects of freestream turbulence is helpful to the heat transfer predictions, but it is incomplete. For example, it does not account for the effects of turbulence scale. Turbulence scale has been shown by VanFossen et al.[28] among others to affect stagnation region heat transfer. Unfortunately, the length scale is not always available along with the heat transfer data. Dullenkopf and Mayle[29] proposed that the effective turbulence intensity account for the blockage, velocity gradient, Reynolds number, as well as the turbulence intensity. Dullenkopf and Mayle[30] proposed a method to include the effect of turbulence scale. Heat transfer predictions in the non-turbulent region would be improved if a correlation similar to that of Smith and Kuethe, but incorporating the factors mentioned, was developed.

The analysis tended to overpredict the suction surface heat transfer in the laminar region, while at times underpredicting the pressure surface laminar region heat transfer. It appears that better agreement with data would be achieved using the Steelant and Dick[11] model for the variation of Tu with freestream velocity. But, the Steelant and Dick relaminarization model underpredicted heat transfer more than the other relaminarization models. This could be due to its influence on the prediction of transition start.

References

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13. ABSTRACT ***(Maximum 200 words)***

An approach to predicting turbine blade heat transfer when turbulent flow relaminarizes due to strong favorable pressure gradients is described. Relaminarization is more likely to occur on the pressure side of a rotor blade. While stators also have strong favorable pressure gradients, the pressure surface is less likely to become turbulent at low to moderate Reynolds numbers. Accounting for the effects of relaminarization for blade heat transfer can substantially reduce the predicted rotor surface heat transfer. This in turn can lead to reduced rotor cooling requirements. Two-dimensional midspan Navier-Stokes analyses were done for each of eighteen test cases using eleven different turbulence models. Results showed that including relaminarization effects generally improved the agreement with experimental data. The results of this work indicate that relatively small changes in rotor shape can be utilized to extend the likelihood of relaminarization to high Reynolds numbers. Predictions showing how rotor blade heat transfer at a high Reynolds number can be reduced through relaminarization are given.

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