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Progress in Modeling of Laminar to Turbulent Transition on Turbine Vanes and Blades

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Abstract

The progress in modeling of transition on turbine vanes and blades performed under the sponsorship of NASA Lewis Research Center is reviewed. Past work in bypass transition modeling for accurate heat transfer predictions, show that transition onset can be reasonably predicted by modified $k-\varepsilon$ models, but fall short of predicting transition length. Improvements in the predictions of the transition region itself were made with intermittency models based on turbulent spot dynamics. Needs and proposals for extending the modeling to include wake passing and separation effects are outlined.

Introduction

The purpose of this paper is to provide a progress report on the modeling of transition on turbine vanes and blades performed under the sponsorship of NASA Lewis Research Center. The interest of NASA Lewis in this topic dates back to the early eighties (Gaugler, 1981). In 1984 a symposium was organized to address the needs and the state of the art of transition in turbines (Graham, 1985). The result of that meeting was the initiation of the Bypass Transition Program, lead by the Heat Transfer Branch at Lewis. The goal of the program was to develop models and provide fundamental understanding leading to improved designs of turbines. The focus of the the program was on heat transfer in the transition regions of blades and vanes under two-dimensional steady and attached flow conditions (Gaugler, 1985). As such, it was applicable mainly to high-pressure turbines, and particularly to those designs that do not utilize film cooling, as the associated fluid injection triggers immediate turbulence and transition is eliminated. It was recognized that experiments, computations, analysis, and modeling, are needed as complementing and augmenting approaches, and that the end product should be improved engineering and turbulence-type models that can be incorporated in the aeropropulsion industry design systems. The program consisted of research work performed in-house at NASA, and of sponsored work in form of grants and contracts, and was presented in annual workshops and summarized in reports and publications.

The major efforts under the bypass transition program were: Experiments on heated flat-plate performed at Lewis by Case Western Reserve University, and experiments on a curved surface at the University of Minnesota. DNS (Direct Navier Stokes Simulation) was performed at NASA Ames. Development and assessment of models were performed at NASA Lewis, University of Texas at Austin, University of Minnesota, and Case Western Reserve University. In addition, transition prediction tools based on PSE (Parabolized Stability Equations) were developed by DynaFlow Inc. These efforts resulted in successful

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Nomenclature

C_f	Skin friction coefficient
K	Pressure gradient parameter, $(\nu/U_e)(dU_e/dx)$
L_{tr}	Transition length
N	Non-dimensional spot formation rate, $N = n\sigma\theta^3/\nu$
n	Spot formation rate
Re_x	Reynolds number based on distance x from leading edge
Re_θ	Momentum thickness Reynolds number
St	Stanton number
T'	Turbulent temperature fluctuation
Tu	Turbulence intensity at free-stream
U_e	Free-Stream velocity
u^+	Streamwise mean velocity in wall units
v'	Turbulence normal velocity fluctuation
x	Distance from leading edge
y^+	Normalized y distance in wall units
α	Spreading angle of spot
β	Velocity of center of spot divided by free-stream velocity
γ	Intermittency
θ	Boundary layer momentum thickness
Λ	Area of spot/square of half width
λ_θ	Pressure gradient parameter, $(\theta^2/\nu)(dU_e/dx)$
ν	Kinematic viscosity
σ	Dimensionless spot propagation parameter

Subscripts:

tr	Transition onset
E	Transition end

generation of experimental and numerical databases, which contributed to understanding of the flow physics, and served as a basis for model development and computational validation.

In 1994 the aero-propulsion industry expressed the need for efficiency improvements of engine components characterized by low Reynolds number flows, such as the low-pressure turbine (LPT). As transition plays a significant role in these flows, it was natural to respond to this need by expanding the scope of the bypass transition program to include separation and unsteady effects (wakes). Accordingly, the program was renamed The Low-Pressure Turbine Flow Physics Program. To facilitate model development work, NASA Lewis chose a management approach which strongly emphasizes collaboration and cooperation between academic and research institutes, industry, and government laboratories. The technical approach continues to consist of combination of experimental work, computation, and analysis and modeling (figure 1).

The major research elements of the LPT program are currently underway. Experimental work is in progress at Lewis with cooperation with University of Toledo, at University of Minnesota, at the US Air Force Wright Laboratory, and is at the planning stage at General Electric Aircraft Engines in Evandale, Ohio (GEAE). Computations are performed by Western Michigan University, NASA Lewis, and CMOTT/OAI (Center for Modeling of Turbulence and Transition/Ohio Aerospace Institute). Additional analysis is done by collaboration between NASA Lewis, Syracuse University and GEAE, and by cooperation between NASA Lewis and Pratt & Whitney. Model development is performed at NASA Lewis, Nyma Inc./Lewis Group, and CMOTT/OAI. Final validation of the models to be developed will be made by implementing them in a CFD code and comparing to results from future low-speed rotating rig experiments.

The significance of the work is mainly in two areas. The first one is a contribution to temperature and life prediction of blades and vanes in the high-pressure turbine. Blade temperature is an important design criterion which greatly affects the design and performance of the whole engine. In addition, life cycle of components, directly affecting maintenance cost is a major factor in design of jet engines. As life of blades is strongly affected by their temperature, its accurate prediction is very important. The second area of significance of this program is in reduction of the performance degradation from takeoff to cruise operating conditions of the low-pressure turbine. The decrease in efficiency between the two operation points is attributed to Reynolds number, which is higher at sea-level takeoff conditions than at altitude cruise conditions. This problem affects mostly the low pressure turbine where up to 2 percent efficiency differentials between takeoff and cruise may be encountered (Presentations at Heat Transfer Branch Bypass Transition Workshop 1993, LPT Flow Physics Workshop, 1995). This gives jet-engine designers the potential for significant efficiency improvements, which translate into fuel and weight savings.

It is then clear that improved modeling and understanding will contribute to more accurate predictions of temperatures and losses, will allow turbine designers to quantitatively compare alternative designs, and will impact overall engine design, performance, cost, and marketability. Advanced CFD methods, such as Direct Navier Stokes Simulation (DNS), or Large Eddy Simulations (LES) has progressed in recent years. These methods, which in principle can address very complex flows, are not yet practical to be used in routine design systems, therefore modeling is still required.

It is clear that the unique flow physics in the turbine must be taken into account in developing modeling methods for adequate predictive capability. Figure 2 depicts the flow issues encountered in turbine blades. The turbomachinery flow environment differs greatly from that of external aerodynamics. In external aerodynamics the incoming flow to the airfoil is normally quiescent. Freestream turbulence levels are in the order of tenth of a percent. In the gas turbine the flow enters the high pressure turbine from the combustor, and the environment is characterized by high levels of turbulence, unsteadiness and flow inhomogeneities. The flow in downstream stages and in the low-pressure turbine is dominated by wake passing and the associated wake turbulence. There is little information available in the open literature based on measurements of the turbulence in actual turbine. The levels of turbine inlet turbulence can only be inferred from limited available measurements of turbulence levels in the exit of the combustor (Zimmerman,1979, Seasholtz *et al*, 1983, Bicen and Jones, 1986, Ames and Moffat, 1990, Ames, 1994)

In low-level turbulence environment the transition process is initiated by linear mechanisms. Freestream disturbances enter the boundary layer via mechanism called Receptivity (see review by Reshotko, 1994), and generate linear instability waves (Tollmien-Schlichting or Görtler waves). The process is followed by a variety of possible nonlinear mechanisms that lead to breakdown of the laminar boundary layer and to the generation of turbulent spots. As the turbulent spots grow, the transitional boundary layer becomes a fully developed turbulent boundary layer. In a highly disturbed environment the linear stage is bypassed and nonlinear stages are triggered directly. This transitional route to turbulence is called Bypass Transition (Morkovin 1978a,b, 1993), and is recognized as the prevailing transition mode in turbomachines. Figure 3 shows the differences between the mechanisms, as reflected by hot wire measurements at low and high levels of freestream turbulence.

The development of the boundary layer over the blade is affected by a multitude of factors. The major factors are the blade Reynolds number, freestream turbulence intensity (and possibly scales, spectra etc.), pressure gradient, and curvature. At low to moderate levels of turbulence there is a laminar region extending from the leading edge, sometimes called the "buffeted boundary layer", "quasi-laminar", or "laminar-like" boundary layer. The oscillations in this region caused by the freestream turbulence consist of linear and nonlinear wave motions, and do not have turbulence characteristics.

The boundary layer may separate, particularly on the suction surface of the blade. Separation may occur in form of a bubble, or as massive separation with no reattachment resulting in large losses. The pressure surface may have cove separation, and small separation bubbles may exist near the leading edge. Often the separation bubble is transitional, where transition starts in the local shear layer that develops at or near the separation point. The reattachment is usually turbulent.

Wake passing was found to have important effects on the flow in turbomachinery (in turbines as well as in compressors), as shown by the comprehensive work of Halstead *et al* (1995). The wake interacting with the boundary layer creates a convected transitional or turbulent patch, trailed by the "calmed" region, a relaxation region between the patch and the the laminar boundary layer. The development of the boundary layer is determined by the interplay between the transition, wake interaction, and separation mechanisms (see also Cumpsty *et al*, 1995). Important additional factors that need to taken into account when wakes are considered are the wake frequency parameter, and the turbine stages geometry. It is also clear that properties of the wake turbulence and of the freestream turbulence play an important role. It seems that in addition to the level of the turbulence, the scales and perhaps the spectra of the turbulence need be considered. It needs to be noted that that there is lack of information on the scales and spectra of freestream and wake turbulence. Some relevant measurements were performed by Ames (1994), in turbine cascade with simulated combustor.

Models are required to predict the onset point of transition and the transition region itself. Separation needs to be predicted, including the location of the separation point and the reattachment point. Transition in a separation bubble under conditions of freestream turbulence has not been properly addressed yet. The effects of wake passing, particularly the calmed region need to be incorporated. For example, when dealing with separation it is important to know if the boundary layer transitions before the separation point, as turbulent boundary layers delay separation. That is where the models for calculating bypass transition in attached flow may be useful.

The following sections focus on describing the progress in modeling which was mostly accomplished under the bypass transition program. Much of the progress will be directly applied in the current challenging LPT Flow Physics Program.

RESEARCH PROGRESS

Transition Onset

Non wake-induced transition onset

Use of two-equation near-wall turbulence models has in general been successful in the prediction of bypass transition onset. Simon and Stephens (1991) used the Jones-Launder turbulence model to predict onset and compared their results with experimental data and the correlation of Abu-Ghannam and Shaw (1980). The comparison of their results with the correlation of Abu-Ghannam and Shaw is good, as shown in figure 4. Simon and Stephens (1991) assumed the transition onset to occur when the numerical computations indicated a rapid increase in turbulence kinetic energy, indicating a non-zero intermittency. This assumption was confirmed (Simoneau and Simon, 1993) by comparison with the DNS calculations of Rai and Moin (1991) shown in figure 5 for the case of zero pressure gradient and 2.6 percent freestream turbulence. Figure 5 shows how the two-equation turbulence model captures the nonlinear disturbance growth which leads to the first sign of turbulent spot formation. Suder, O'Brien and Reshotko's (1988) single-wire measurements within the boundary layer indicated spot initiation at a boundary layer turbulence level of 3.5 percent regardless of the path to transition (high or low freestream turbulence). This experimental result appears consistent with the calculations of Simon and Stephens (1991) and Rai and Moin (1991) shown in figure 5.

Figure 5 suggests that, below a certain critical Reynolds number, amplification of disturbances is not significant. This was the basis for the assumption made by Schmidt and Patankar (1988) in their development of a turbulence model for transition and the basis used by Simon and Stephens (1991) for initializing the calculations for disturbance energy shown in figure 5. The assumption made by the above authors was that this critical Reynolds number is close to the critical Reynolds number for linear instability.

Other experimental and analytical values for transition onset are given in figure 4. The experimental transition onset values of figure 4 are based on the zero intermittency point, while the computational transition onset values are based on zero intermittency and the minimum Stanton number. Figure 4 shows some experimental transition onset results given in the survey report of Volino and Simon (1991) and some examples of the result of transition onset calculations utilizing a number of turbulence models developed at the University of Texas at Austin. Figure 4 shows the general applicability of turbulence models for predicting transition onset. Turbulence models developed at the University of Texas at Austin (Crawford, 1991) called the Texas model (TXM) and the Multi-Time-Scale (MTS) model have the potential of improved simulation of the transition region. A multiple-scale $k-\varepsilon$ turbulence model developed by Wu and Reshotko(1996) was found to predict transition onset reasonably well.

The K.-Y. Chien turbulence model (1982) results shown in figure 4 were found by Stephens and Crawford (1990) to give a premature value for transition onset. They explained that this is because the damping function of the Chien model is dependent only on the boundary layer normal distance and that an improved onset prediction is obtained when the damping function is dependent on the turbulent Reynolds number. The inability of the K.-Y. Chien model to simulate transition onset was also found by the heat transfer Navier-Stokes calculations of a turbine blade by Ameri and Arnone (1992).

The effect of curvature on transition onset at low freestream turbulence is summarized from the experimental work of Wang (1984) and Kim and Simon (1991) in figure 6. In figure 6 the pressure surface of a turbine blade is represented by the concave surface and the suction surface is represented by the convex surface. As indicated in figure 6 , a convex surface when compared to a flat surface will delay transition onset and a concave surface compared to a flat surface will shift transition onset upstream. The differences in onset location, based on the minimum in the Stanton number, for a convex surface and a flat surface diminish as the freestream turbulence increases (figure 7). This suggests that for the freestream turbulence levels encountered in an engine, curvature plays a minor role in the value of transition onset on the suction surface of a turbine blade.

Volino and Simon (1991) noted little effect of favorable pressure gradient on the momentum Reynolds number of transition. This is in agreement with findings of Abu-Ghannam and Shaw (1980).

Stuckert and Herbert (1992) compared their Parabolized Stability Equations (PSE) approach with the experimental data of Sohn and Reshotko (1991) as shown in figure 8. The onset of transition as defined by the minimum Stanton number is predicted very well by the PSE method. Volino and Simon (1991) compared the zero intermittency point with the minimum Stanton number (used by some as a definition for transition onset) and determined that the minimum Stanton number is located somewhat downstream of the zero intermittency point. This was also noted by Simon and Stephens (1991).

Wake-induced transition onset

A reasonable estimate may be made of wake-induced transition onset by using the local value of the wake turbulence intensity in the Abu-Ghannam and Shaw correlation. However, the actual transition onset is generally lower than that predicted with the correlation of Abu-Ghannam and Shaw (Orth, 1993), which approaches a momentum thickness Reynolds number of 163 at high freestream turbulence. In general, the momentum thickness Reynolds number for onset has a range of 90 to 150. Work needs to be done to establish a reliable prediction of wake-induced transition onset.

Transition onset on a separated shear layer

As the blade Reynolds number is reduced, transition via laminar separation becomes more prevalent than bypass transition. It is unlikely that transition on the separated shear layer will begin with turbulent spots as occurs on an attached boundary layer (Gleyzes, *et al*, 1985). Transition correlations, such as Roberts (1975) and Mayle (1991), have been developed in terms of the distance from onset of separation to the end of transition. It is often assumed that the momentum thickness Reynolds number changes very little between separation and transition onset.

Effect of calmed region on transition onset

The calmed region is that region behind a turbulent spot or spots, generated by a freestream or wake disturbance, that has the characteristic of decreasing but still elevated wall shear stress producing a condition that suppresses new instabilities or turbulent spots. Only when the calmed region returns to its original non-turbulent level does the possibility exist for new turbulent spot onsets to begin. This effect can be seen in the hot-wire interrogation of wedge flow by Schubauer and Klebanoff (1956) shown in figure 9. Figure 9 shows how a new spot does not begin until the effects created by the old spot diminish. Schubauer and Klebanoff state that transition will not occur in this region they label the "recovery trail". This recovery trail or calmed region is seen in the time trace of figure 9 as a gradual decrease in the signal with time. The effect of the calmed region is to lengthen the transition region, a fact that will change the expected profile losses on a turbine or compressor blade, as documented by Halstead, *et al* (1995).

Transition Region

Non wake-induced

Figure 10 shows conditionally sampled velocity profiles in the transition region of a flat plate as reported by Sohn, Reshotko and Zaman (1991). Figure 10 shows the departure from a Blasius profile as an indication of the transition region which occurs after transition onset. The deviation of the non-turbulent profiles from the Blasius curve increases with intermittency, while the turbulent part of each profile approaches the fully- turbulent boundary layer profile as intermittency increases. The deviation of the non-turbulent part from a Blasius profile with increased intermittency is attributed by Kim and Simon (1991), as well as by Sohn and Reshotko (1991), to a post-burst relaxation period (calmed region) required for a disturbance in the non-turbulent part of the flow to damp-out. With an increase in the number of turbulent spots, or increased intermittency, there are more post-burst relaxation periods included in the non-turbulent part of the flow. Figure 10 also suggests that the transition region cannot be described as a simple intermittency weighted linear combination of Blasius and fully-turbulent boundary layer profiles, as postulated by Dhawan and Narasimha (1958).

The momentum thickness Reynolds number at the end of transition, as compared with the correlation of Abu-Ghannam and Shaw (1980), is given in figure 11. Figures 4 and 11 demonstrate the strong effect freestream turbulence intensity plays, although it is expected that the spectra and length scale of the freestream turbulence will be needed to further refine the turbulence effects. While $k-\varepsilon$ turbulence models perform well in the prediction of transition onset (figure 4), they generally give an underprediction of transition length (figure 11). A reason for this may be found in the work of Volino and Simon (1993). Volino and Simon (1993) applied an octant analysis to the experimental data to analyze the difference in structure between turbulent and transitional flows. They indicate that transitional boundary layers show incomplete mixing or incomplete development of turbulence with a domination of the large scale eddies. This is attributed to the incomplete development of the cascade of energy from large to small scales. Based on this observation, it is stated that the standard $k-\varepsilon$ turbulence model does not comprehend the physics of the transition region and what is needed is a model that will comprehend both large and small scales separately. This would require a modified $k-\varepsilon$ equation with perhaps two equations for the turbulent kinetic energy (k); one $k-\varepsilon$ equation for the large scale eddies and one for the small scale eddies. Such a multi-time-scale (MTS) model for application to transition flows has been implemented by Crawford (1992). This model is an evolution of two-scale $k-\varepsilon$ models developed by Hanjalic, Launder and Schiestel (1980) and Kim (1990). Numerical calculations performed by Chen (1994) at the University of Texas (figure 12) show promise that the MTS model is capable of simulating the transition region for turbulence levels greater than two percent. A similar approach utilizing a multiple scale $k-\varepsilon$ turbulence model was reported by Wu and Reshotko (1996). One of their results (figure 13) for the Reynolds analogy factor shows an early transition but agrees well in the fully turbulent flow. The Reynolds analogy results of figure 13 reflect the unheated starting length of 1.375

inches of the experiment.

Schmidt and Patankar (1988) attributed the underprediction of the transition length to the production term of the turbulent kinetic energy equation. They modified the production term to make predictions consistent with experimental results. Figure 14 demonstrates the improved prediction of transition as a result of modifying the production term.

A DNS calculation of transition on a heated flat plate, for a freestream turbulence of 2.6% , was performed by Madavan and Rai (1995). Madavan and Rai used a high-order-accurate finite-differencing approach for the direct numerical simulation of transition and turbulence. Figures 15 and 16 compare the skin friction and Stanton number experimental results of Suder, O'Brien and Reshotko (1988), Sohn and Reshotko (1991), and Blair (1983), with the DNS results. There is reasonable agreement between experiment and DNS results, with the agreement being better for the heat transfer results. The results for the Reynolds analogy were shown in figure 13. There is good agreement in the laminar and turbulent regions. The difference between calculation and experiment in the transition region is due to the rapid increase in the calculated skin friction (figure 15). Sufficient confidence has been established with the DNS approach that the resulting numerical base is seen as valuable for the development and testing of turbulence models applicable to bypass transition. As a point of interest, the experimental work of Sohn and Reshotko (1991) reported negative values for the turbulent heat flux ($\overline{v'T'}$) near the wall in the transition region. The attempts to experimentally determine the reason for this anomaly (Sohn, Zaman, and Reshotko, 1992) have not been successful. The DNS results of Madavan and Rai show no evidence of negative turbulent heat flux for either the transition or turbulent region. This discrepancy demonstrates the challenges associated with validating results of hot-wire measurements near the wall.

Simon and Stephens (1991), following the concept of Schmidt and Patankar, utilized stability considerations for determining the location of the initial profiles in the numerical calculations, and developed a basis for utilizing intermittency in transition calculations. They followed the method of Vancoille and Dick (1988) to develop conditional averaged turbulence model equations for heat transfer. This approach is felt to be better than a global time average approach which does not take into account a transition zone consisting of turbulent spots surrounded by laminar-like fluid. The method of Simon and Stephens (1991) assumes the universal intermittency relationship of Narasimha (1957) which compares favorably with the experimental data as presented by Volino and Simon (1991) and shown in figure 17. As can be seen on figure 17, a determination of intermittency requires knowledge of the transition length. This was done by Simon and Stephens by utilizing the approach of Narasimha (1985) which expresses the transition length in terms of a nondimensional spot formation rate (N). Narasimha (1985) demonstrates that N reaches a constant value at the higher turbulence levels. The experimental value of N used by Simon and Stephens was compared to the result of an analysis by Simon (1994). The following equation of Simon (1994) relates N to turbulent spot characteristics:

$$N = \left(\frac{\Lambda \tan\alpha}{\beta}\right)^2 \quad 8.1 \times 10^{-4} \tag{1}$$

The analytical value of N reported by Simon (1994) using equation (1) is a constant of 0.00029 (zero pressure gradient), in agreement with the experimental value. The use of N permits a determination of transition length by means of the following equation reported by Simon and Stephens (1991):

$$Re_{L_{tr}} = \frac{2.15}{\sqrt{N}} Re_{\theta_{tr}} \tag{2}$$

Transition calculations were made by Simon (1994) utilizing equations (1) and (2), and the intermittency path equation of Narasimha (1957) with the TEXSTAN code of Crawford (1985). The resulting calculations are compared to the data of Blair and Werle (1980, 1981) in figures 18 to 20 for zero and favorable pressure gradients. Figure 18(a) is an example of the abrupt onset of transition that was obtained when intermittency was not used. The value of using intermittency for improvement of the transition model is clearly demonstrated. There is generally good agreement between experiment and prediction. It is interesting to note, according to the calculations, that the boundary layer acts as if it were a laminar boundary layer up to a significant value of the intermittency (figure 19). This is consistent with the measured velocity profiles of Sohn, O'Brien and Reshotko (1989) which showed a laminar-like overall profile in the transition region for intermittency values up to 0.34 at 1 percent freestream turbulence.

Yang and Shih (1992) Report an improvement over the Launder-Sharma model (Launder and Sharma, 1974) by the use of a new low-Reynolds-number turbulence model and an intermittency weighing factor. The intermittency weighing factor used by Yang and Shih is related to an intermittency factor defined by the variation of the boundary layer shape factor through the transition region. The intermittency weighing factor is used to modify the calculated eddy viscosity in the transition region. The result is an improvement over the Launder-Sharma model, as shown in figure 21. In addition, Yang and Shih point out that a drawback of the Launder-Sharma model is its inability to perform as well as other models for fully-developed turbulent boundary layers.

Solomon, Walker and Gostelow (1995) propose a new calculation method for intermittency that allows for adjustment of spot growth parameters in response to changes in the local pressure gradient. This especially valuable for turbomachinery flows where large changes in pressure gradient occur within the transition region. The method permits a more accurate value of intermittency for use in eddy viscosity methods such as the Simon and Stephens (1991) method noted above. Solomon, *et al* (1995) present the following equation:

$$\gamma = 1 - \exp\left[-n \int_{x_t}^{x} \left(\frac{\sigma}{\tan\alpha}\right) \left(\frac{dx}{U_e}\right) \int_{x_t}^{x} \tan\alpha \quad dx\right] \tag{3}$$

The spot formation rate (n), spot propagation parameter (σ) and turbulent spot spreading angle (α) are presented as correlations (Gostelow *et al*, 1994, 1995) in terms of a pressure gradient parameter (λ_θ). The spot formation parameter is calculated from the correlation for the non- dimensional spot formation rate parameter (N). This correlation is a function of pressure gradient and freestream turbulence. A comparison of the Gostelow *et al* (1994) correlation for N at a freestream turbulence of 2 and 5 percent is made with equation (1) in figure 22. The calculation with equation (1) employed the spot spreading angle correlation of Gostelow, *et al*(1995). A value of $\Lambda = 2.88$ was used in equation (1), and was determined with the correlations for turbulent spot spreading angles and velocities for a zero pressure gradient. Figure 22 shows a fair comparison between equation (1) and the Gostelow correlation. The divergence at the higher adverse pressure gradients is expected as the transition region for these pressure gradients is more governed by streamwise interaction of turbulent spots (Walker, 1987) while equation (1) was derived assuming lateral interaction of spots. The value of N in figure 22 for a zero pressure gradient, using equation (1), is 66% greater than indicated above (Simon, 1994), due to the spot properties given by Gostelow.

Wake-induced transition

Addison and Hodson (1991) state that wake-induced transition can be treated in the same manner as steady transition. Therefore, it can be assumed that turbulent spots created by the presence of unsteady disturbances, and the resulting intermittency, can be described by equation (3) above and the steady state correlations of Gostelow, *et al* (1994, 1995). It would appear that the computational method of Solomon, Walker and Gostelow (1995) is applicable here. The other approach is to use intermittency equations developed, for wake-induced transition, by Mayle and Dullenkopf (1989, 1991) and Hodson, *et al* (1992). In either case the key variable required for intermittency calculations is the location of transition onset. As indicated above, more work is needed in the area of wake-induced transition onset.

Separated-flow transition

Mayle (1991) provides an excellent summary of separated-flow transition and notes its importance to the design of low-pressure turbines. The resulting bubble formation of separated flow can have a significant effect on the aerodynamics and heat transfer of turbines. There is a need to predict laminar boundary layer separation with turbulent reattachment, determine the bubble's displacement effect on the mainstream flow and whether the bubble will "burst" and dramatically increase the blade losses. It is important to know something of the separated layer transition process for a determination of bubble length and "bursting". Some progress toward meeting this need was provided by a NASA sponsored experimental study of the bubble formation process for a "short" laminar bubble (Morin and Patrick, 1991). Morin and Patrick provide detail measurements of a laminar separation bubble and compare the measured transition length to existing correlations. Figure 23 shows a comparison of the experimental transition length with a modified Roberts correlation (Davis, Carter, and Reshotko, 1985). There is excellent agreement in the limited range of freestream turbulence used. Walker (1987) indicates that the transition length for a separated laminar shear layer should be less than that for an attached boundary layer and greater than that predicted by his model for a minimum transition length at zero pressure gradient. His correlation of the minimum transition length compares favorably and slightly higher than the experimental data as shown in figure 24. The transition length for an attached boundary layer, as predicted by Dhawan and Narasimha (1958) is about an order of magnitude greater than the measured values on a separated laminar shear layer. Walker's analysis is based on the interaction of turbulent spots in the streamwise direction. Further study is required to determine the applicability of a turbulent spot model on a separated laminar shear layer.

Effect of the calmed region

An excellent documentation of the effect of the calmed region on transition and separation is provided by the experimental and numerical work of Halstead, *et al* (1995). Their results show the suppression of laminar separation and the delay of transition onset as noted above. The separation that was expected on a compressor or turbine blade did not occur due to the elevated shear stress produced by calming. The effect of the calmed region to extend the transition zone and suppress separation can have a profound impact on the design of low-pressure turbines. The interplay between wake frequency and the calming region is interesting. Halstead, *et al*, have observed on a compressor blade that when the wake frequency is high enough, so that the calming region does not decay to zero before the next wake, bypass transition dominates. When the wake frequency decreases, the calming effects also decrease, and separated flow transition dominates. Orth (1993) noted that laminar calmed regions, behind turbulent patches created by wakes, existed far beyond the location at which the undisturbed boundary layer is fully turbulent. The work of Halstead, *et al* (1995), as well as of other researchers, points out the need for additional studies of the calmed region and for the development of unsteady models that will comprehend the effect calming has on transition and separation. This need is best expressed with a quote from Halstead, *et al* (1995); "Improvements in modeling the essential physics of turbulent spot formation and the associated calmed effects as well as addressing flow separation issues would likely improve predictions".

CONCLUDING REMARKS

This research progress report has demonstrated the importance of a team approach, with the appropriate mix of experimental and analytical skills, for the purpose of understanding and modeling the complex physics occurring on a turbine blade. Sufficient progress has been made in the understanding and modeling of Bypass Transition so that specific recommendations may be made for modeling non wake-induced transition onset. Two-equation turbulence models appear to capture the growth of non-linear disturbances in bypass transition and are capable, with appropriate damping functions and constants, of predicting transition onset. However, these models under-predict the transition length unless, (1) provision is made for the intermittent nature of the transition region, or (2) a modification is made for the rate of turbulence production, or (3) a multi-scale model is used to account for the incomplete nature of the turbulent energy cascade in the transition region. The need for a multi-scale turbulence model has been confirmed by an analysis of the experimental data.

A recommendation is made for the use of the intermittency calculation approach of Solomon, Walker and Gostelow (1995) in the transition region to permit the proper turbulent spot growth as a function of the local pressure gradient on a turbine blade. It has been demonstrated that the use of intermittency in the numerical calculations is the most effective approach for modeling of the transition region.

Direct Numerical Simulation (DNS) has proven to be a very powerful tool for understanding the physics, supporting and guiding the experimental results and forming a data base for the development and testing of transition turbulence models. Results obtained with DNS compare very well to the experimental results.

A great deal more effort needs to be applied to the understanding and modeling of the effect that the calmed region has on transition and separation, transition on a separated shear layer, and wake-induced transition.

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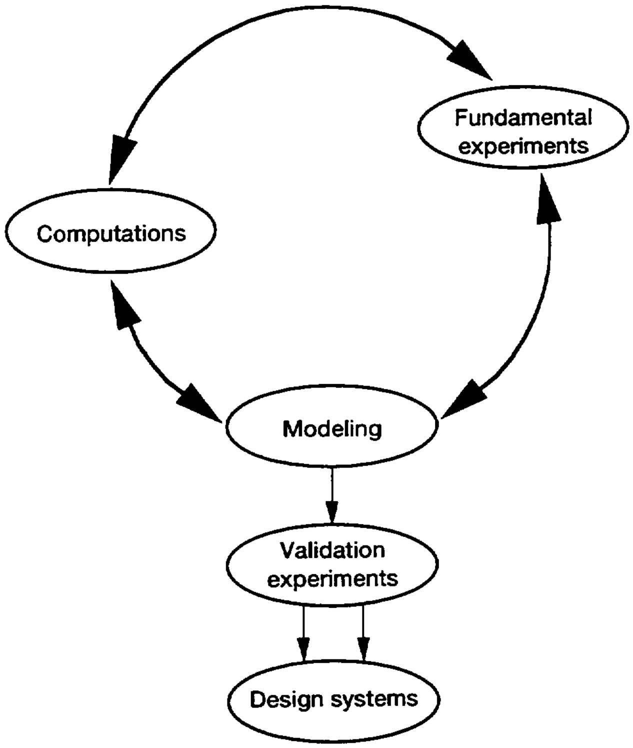

Figure 1.—Low pressure turbine flow physics program.

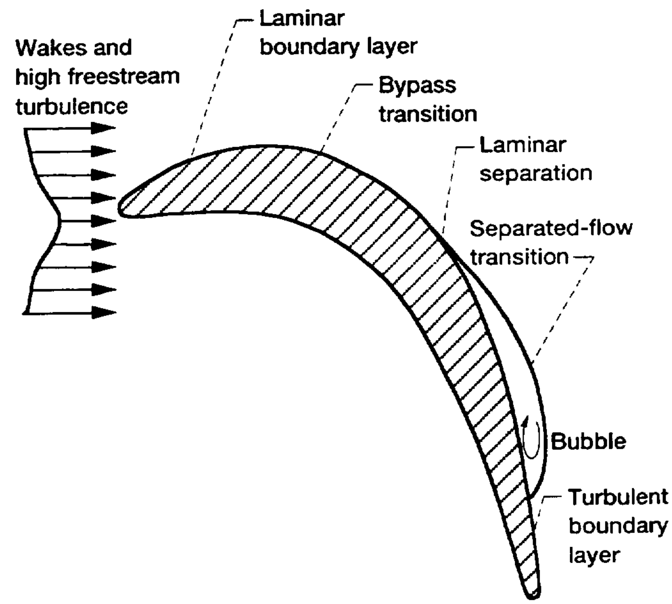

Figure 2.—Transition events on a turbine airfoil.

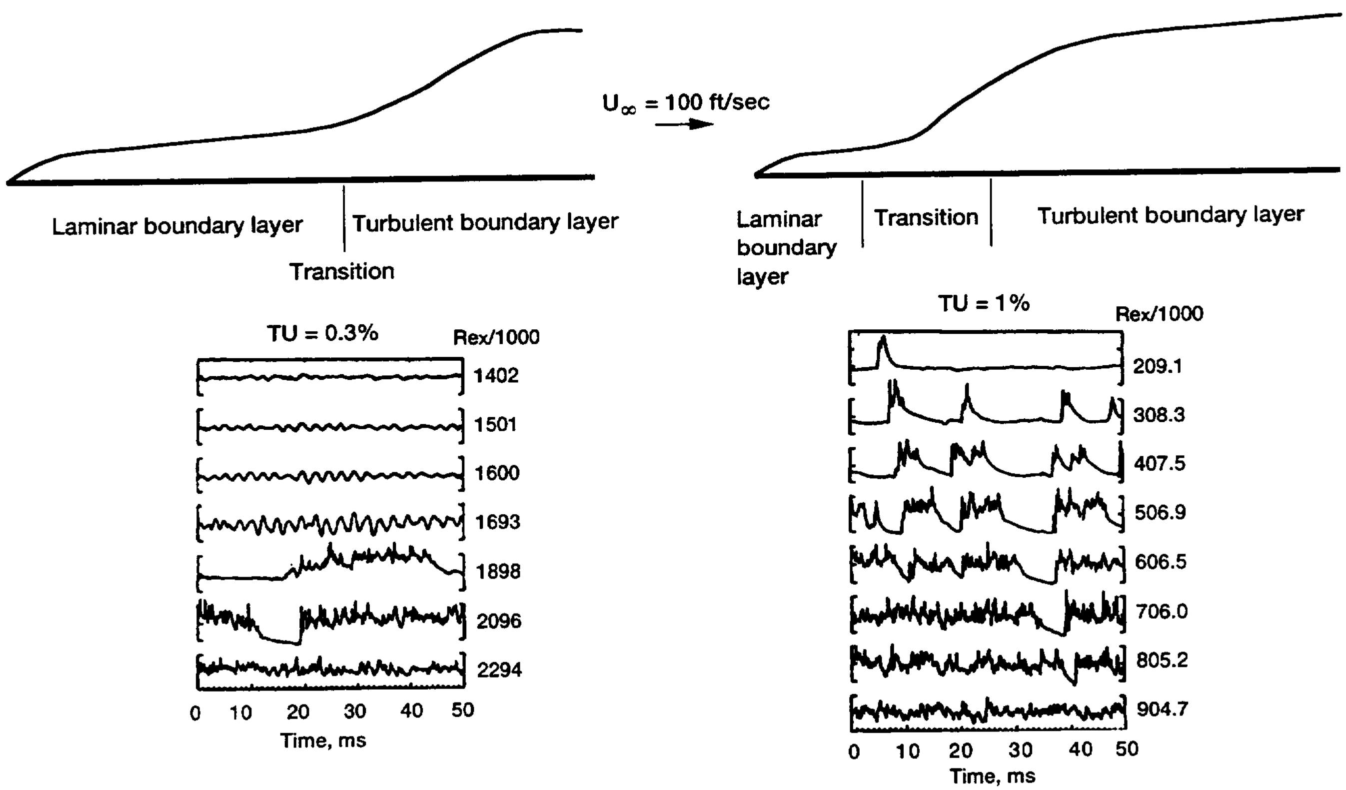

Figure 3.—Linear versus bypass path to transition, from Suder, O'Brien, Reshotko (1988).

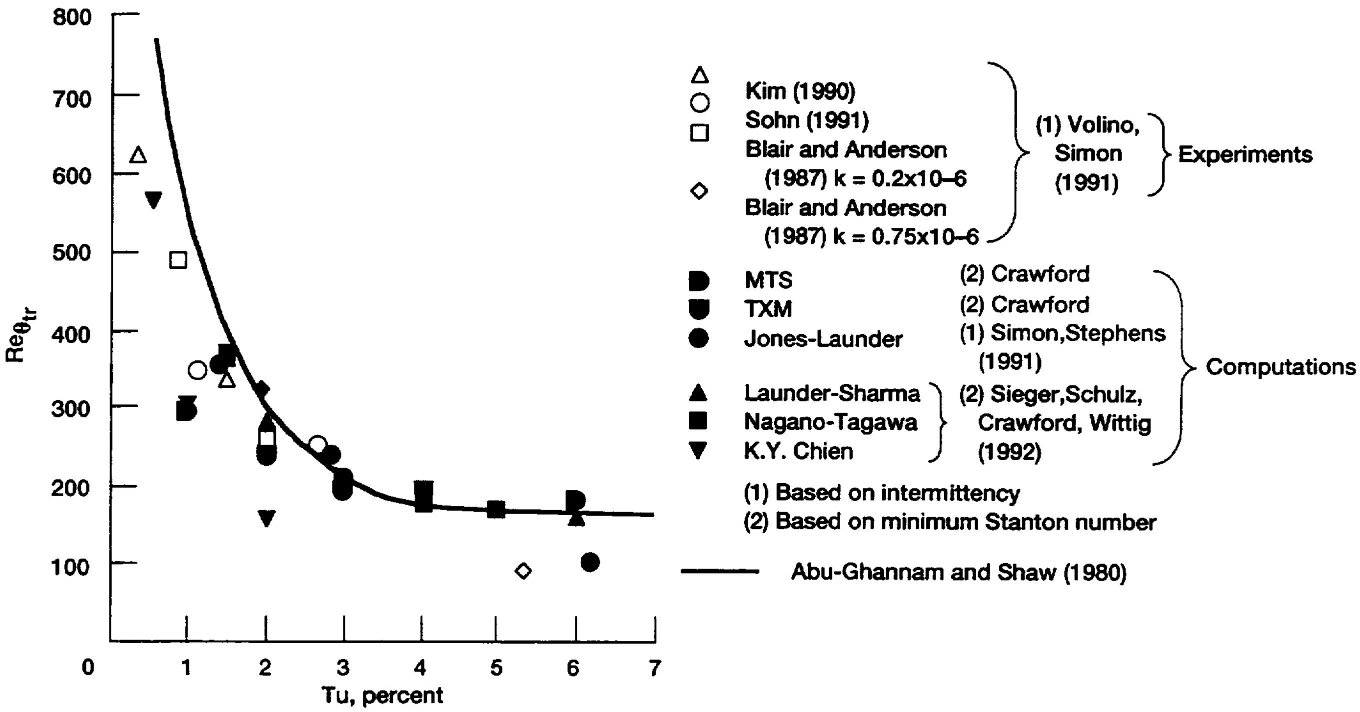

Figure 4.—Computed and experimental momentum thickness Reynolds number for transition onset.

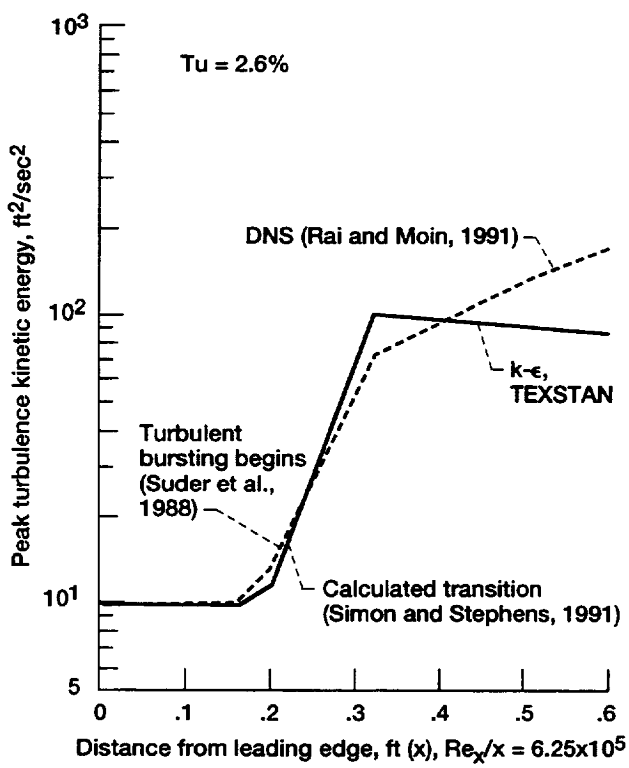

Figure 5.—Comparison of computed disturbance energy from computations based on a k-ϵ model and on direct numerical simulation (DNS) for bypass transition (Simoneau and Stephens, 1993).

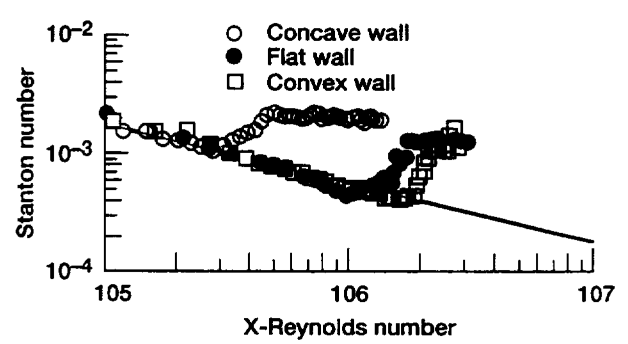

Figure 6.—Effect of streamwise curvature on bypass transition. Wall radii of curvature 90-100 CM; free-stream distribution level 0.6-0.7 percent. (Wang, 1984; Kim and Simon, 1991).

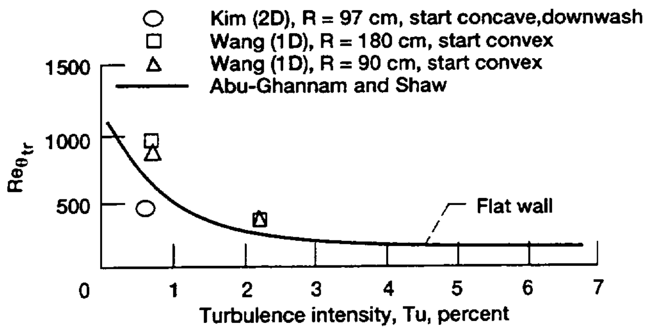

Figure 7.—Transition start based on St, curved wall cases. (Volino and Simon, 1991).

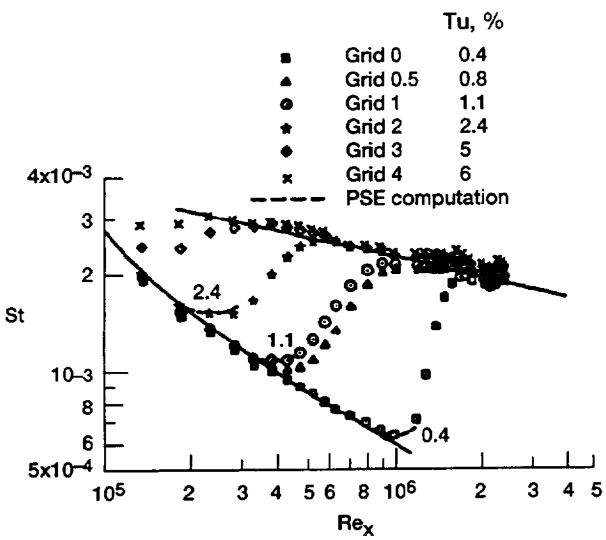

Figure 8.—Onset prediction using PSE approach (Stuckert & Herbert, 1992) Data of Sohn & Reshotko (1991).

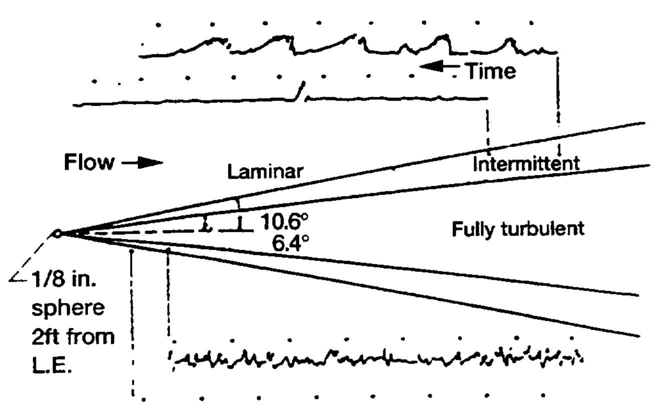

Figure 9.—Turbulence wedge produced by three-dimensional roughness element. (Schubauer & Klebanoff, 1956)

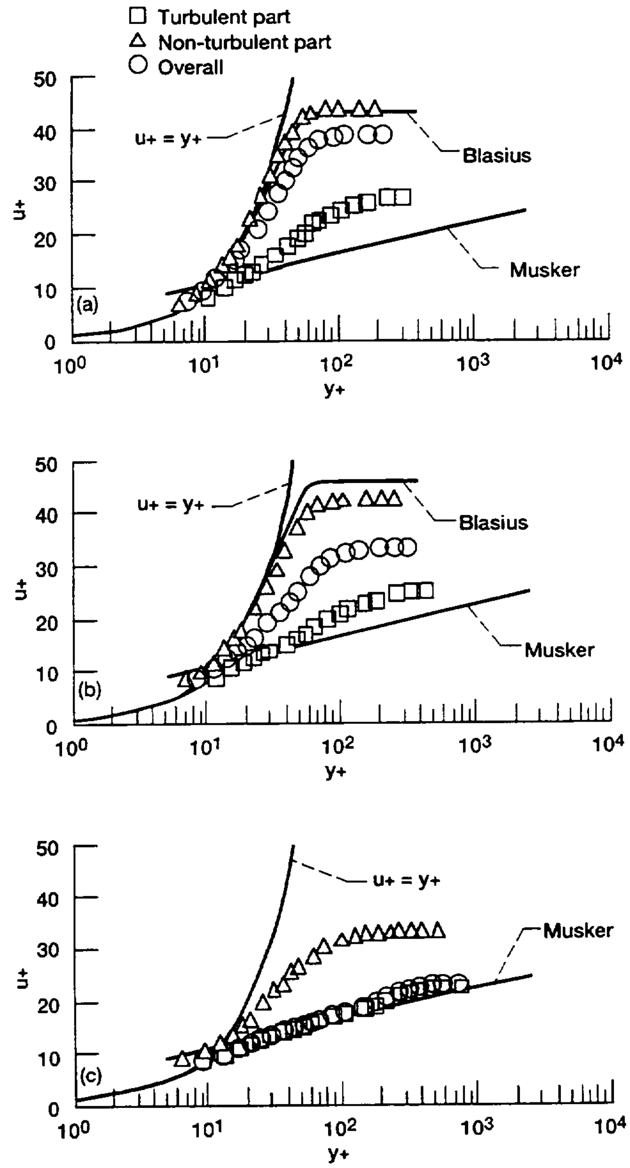

Figure 10.—Conditionally sampled mean velocity profiles in wall units. (Sohn, Reshotko and Zaman, 1991). (a) Grid 1, x = 9 in., Re_x = 421000, γ = 0.34. (b) Grid 1, x = 11 in., Re_x = 507000, γ = 0.55. (c) Grid 1, x = 17.5 in., Re_x = 841000, γ = 0.97.

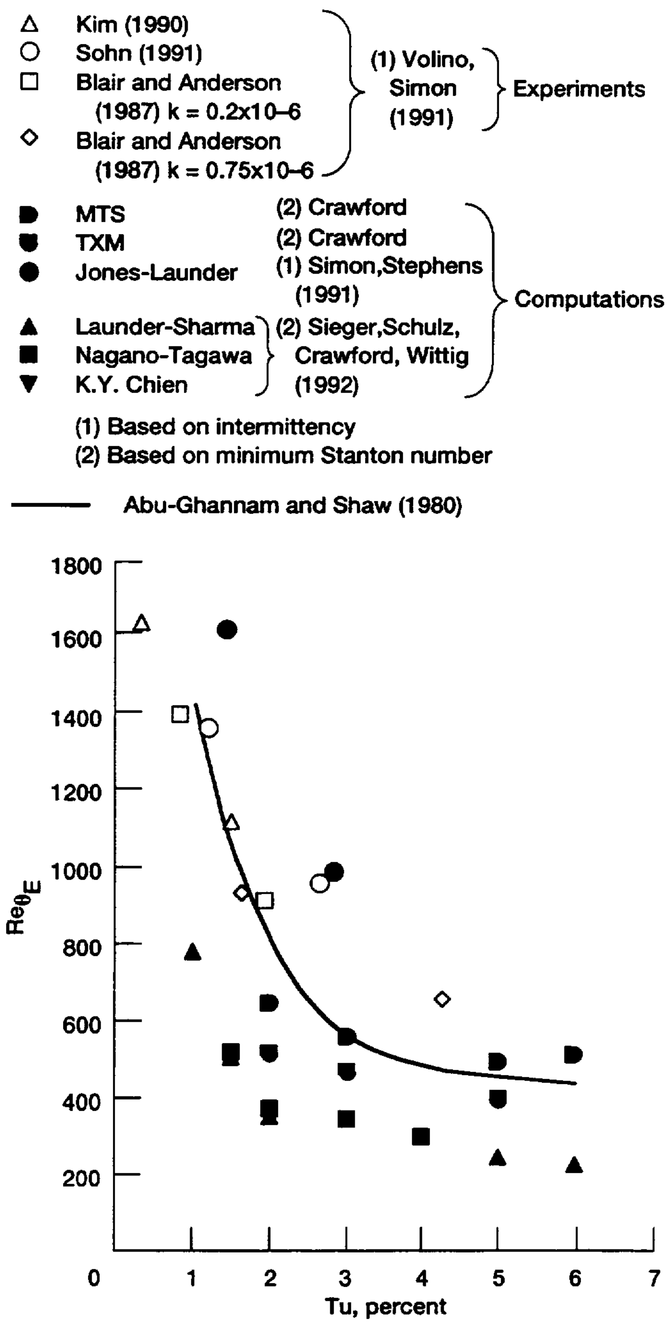

Figure 11.—Computed and experimental momentum thickness Reynolds number for transition end.

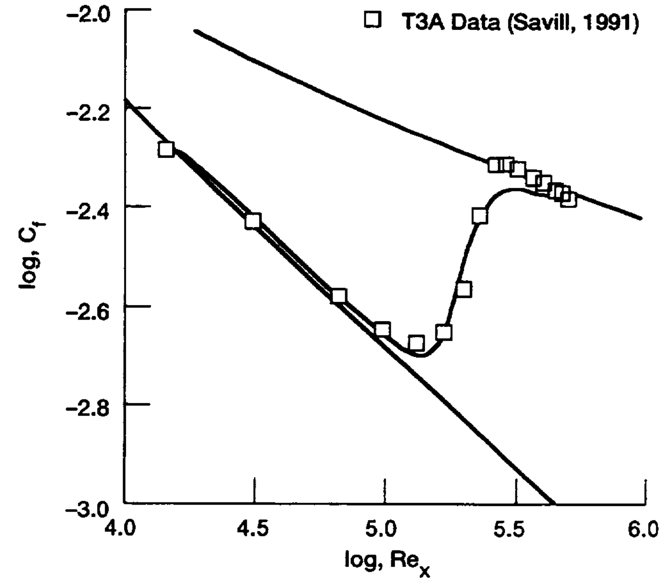

Figure 12.—The numerical prediction of transition flow using MTS model compared with experimental data of T3A (Chen, 1994)

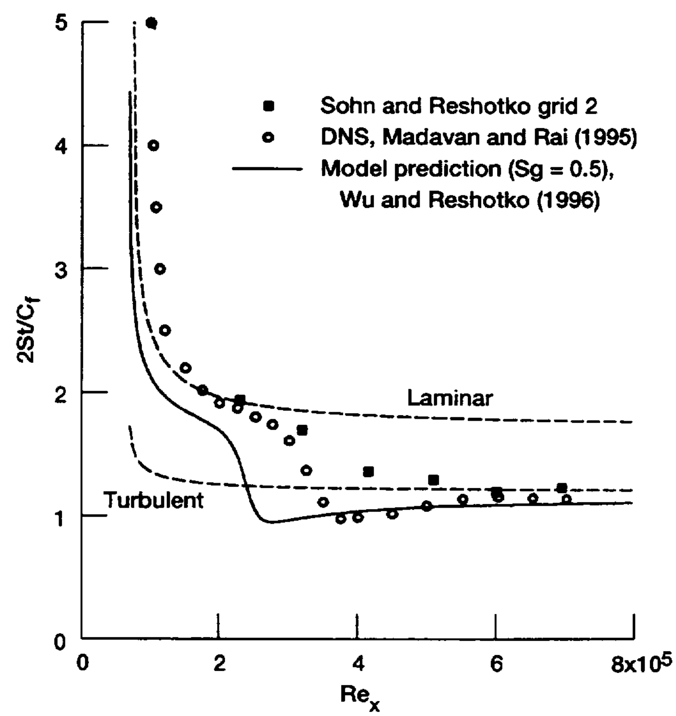

Figure 13.—Comparison of the predicted Reynolds analogy factors with the experimental data of Sohn and Reshotko (1991) and the DNS results of Madavan and Rai (1995).

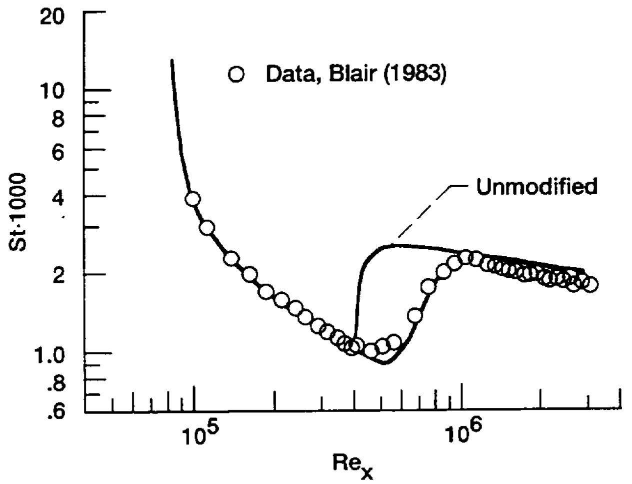

Figure 14.—Effect of production term modification on the calculated Stanton number. Tu = 1.4% (Schmidt and Patankar, 1988).

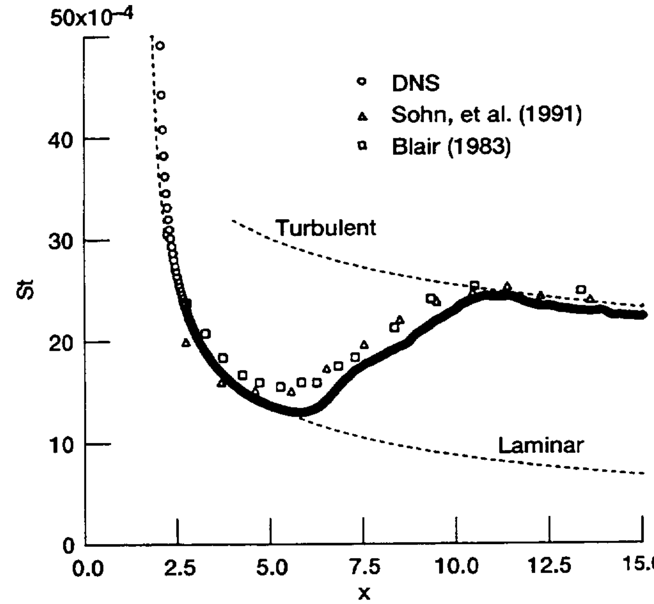

Figure 16.—Computed Stanton number distribution (Madavan and Rai, 1995).

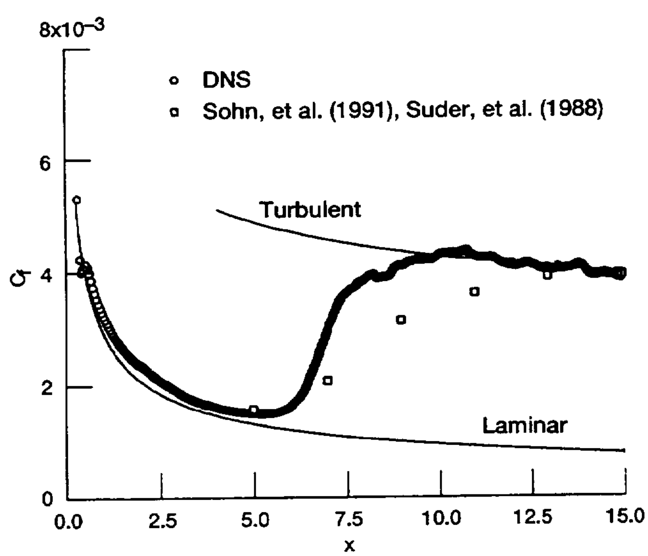

Figure 15.—Computed skin friction distribution (Madavan and Rai, 1995).

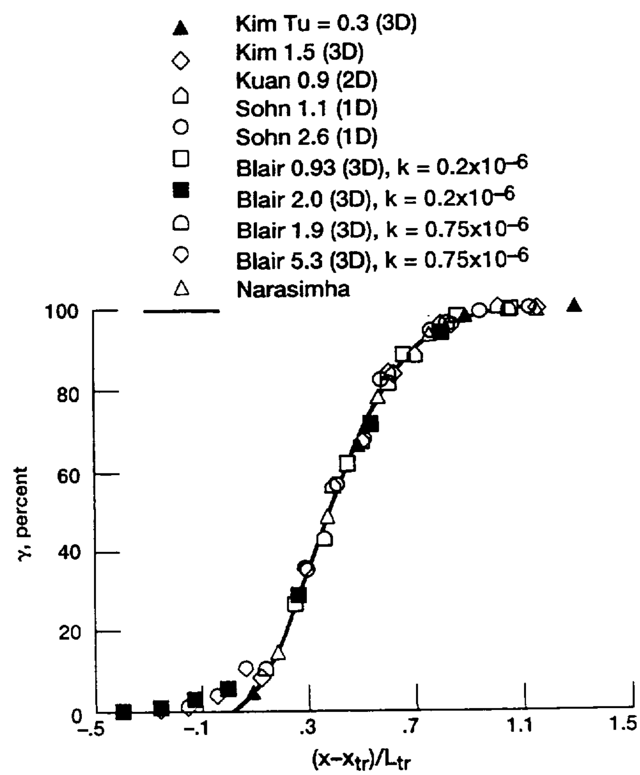

Figure 17.—Intermittency (Volino and Simon, 1991).

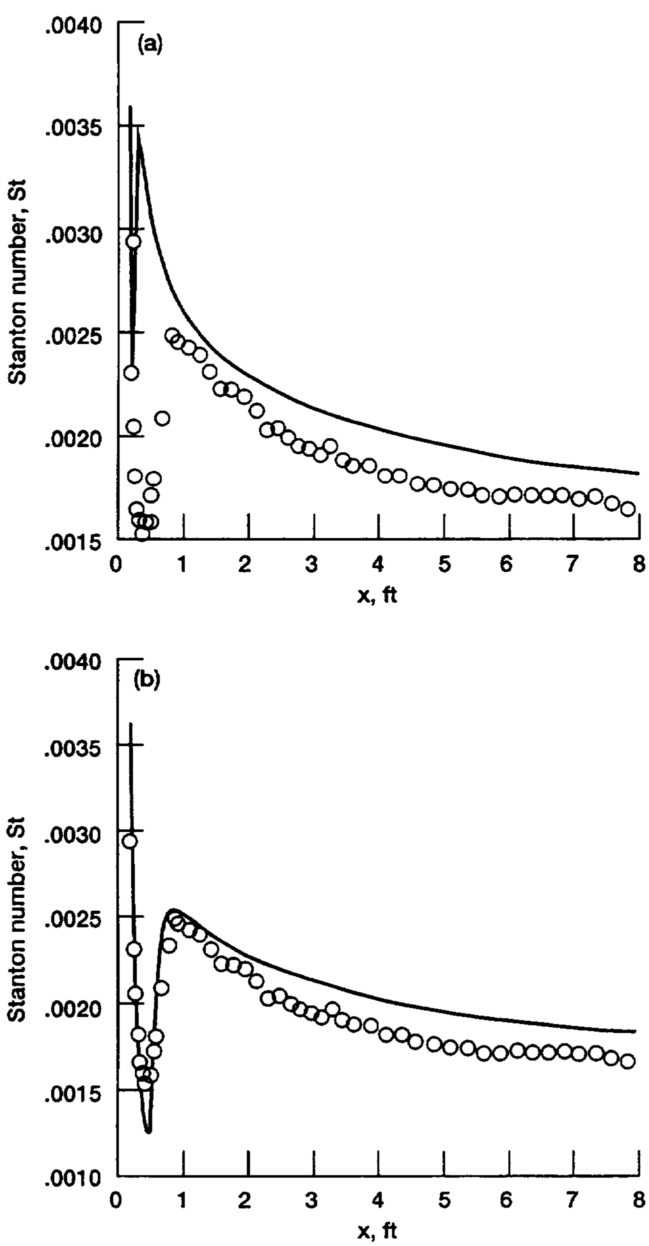

Figure 18.—Use of intermittency to model transition region. (a) Without intermittency, Tu = 2.8%. (b) With intermittency, Tu = 2.8%.

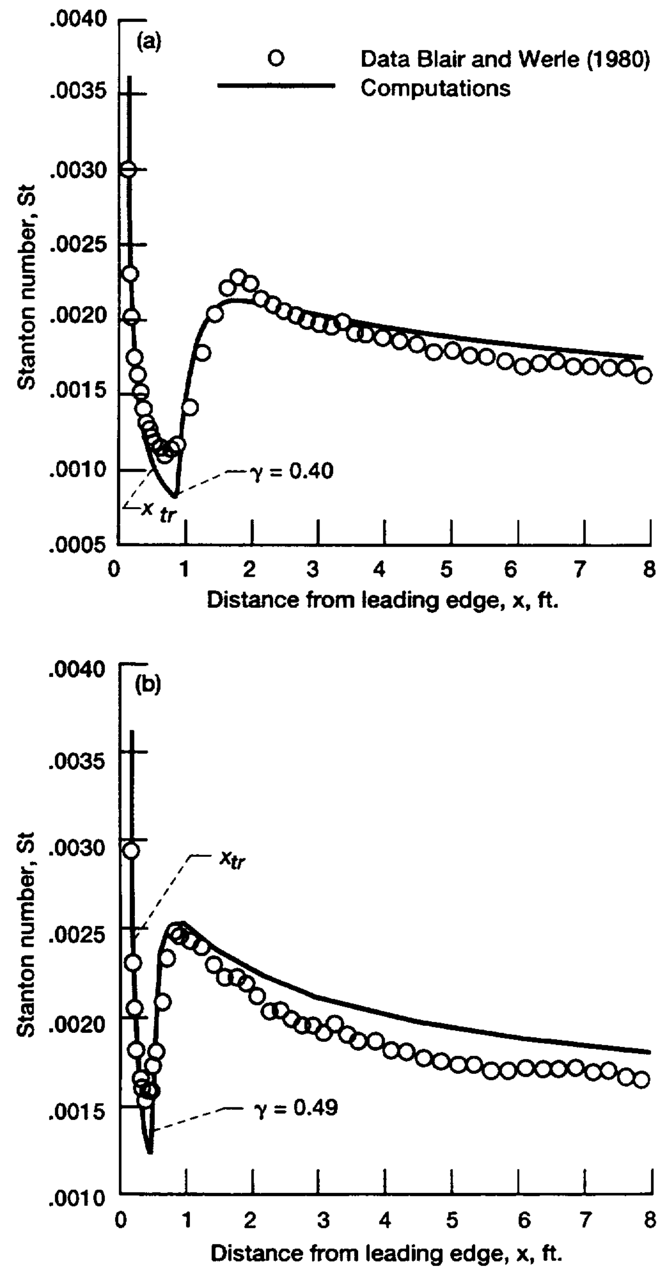

Figure 19.—Comparison of prediction with experiment (zero pressure gradient, $\alpha = 11°$, $\beta = 0.65$). (a) Total turbulence intensity, Tu, 1.4 percent. (b) Total turbulence intensity, Tu, 2.8 percent.

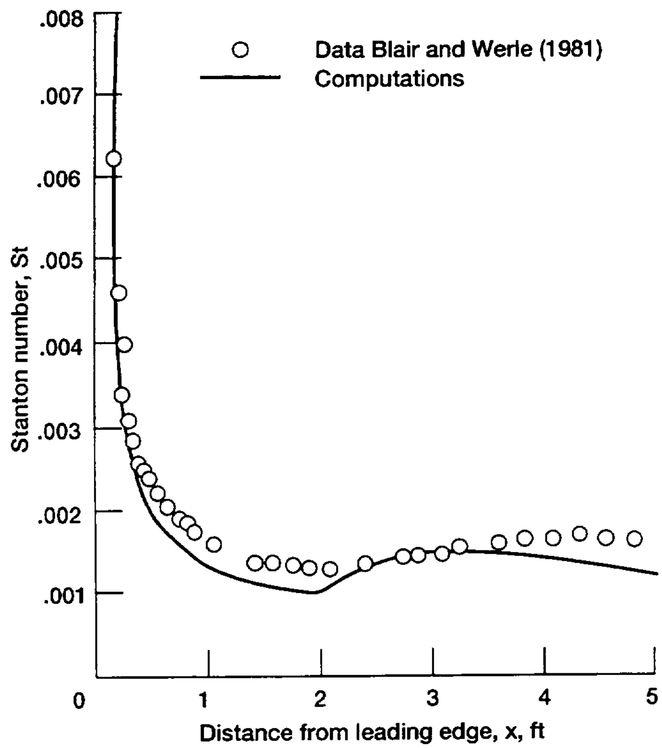

Figure 20.—Comparison of prediction with experiment (favorable pressure gradient, $k = 0.75 \times 10^{-6}$, $\alpha = 5°$, $\beta = 0.8$). Total turbulence intensity, Tu, 2.2 percent.

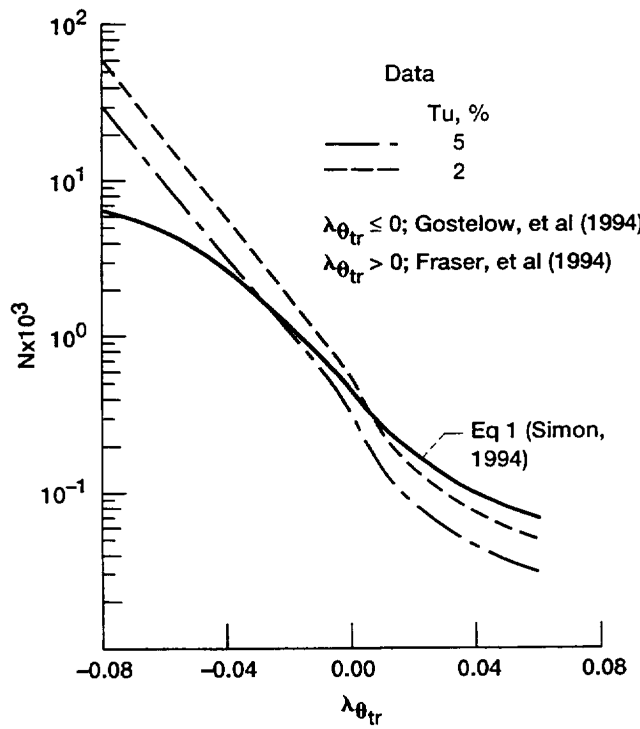

Figure 22.—Non-dimensional spot formation rate parameter.

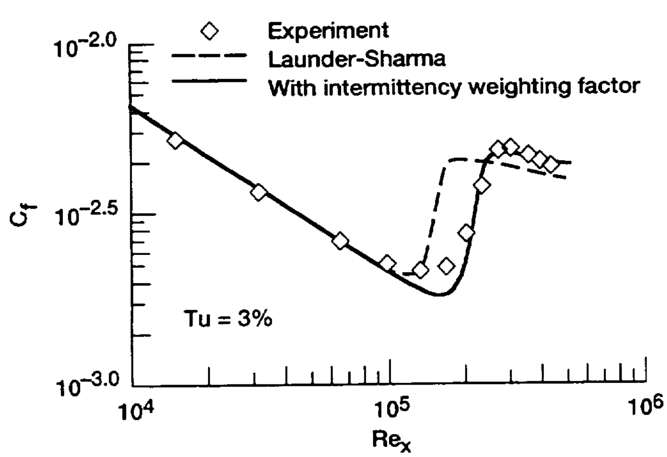

Figure 21.—Use of an intermittency weighting factor in computations. Skin friction variation for T3A. (Yang, 1992; Yang and Shih, 1992).

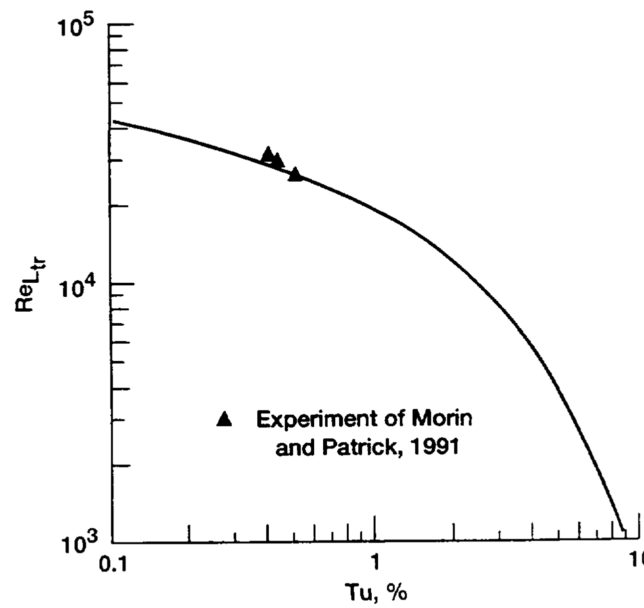

Figure 23.—Measured transition length of a separated laminar shear layer compared to modified Roberts' correlation (Davis, Carter, Reshotko, 1985)

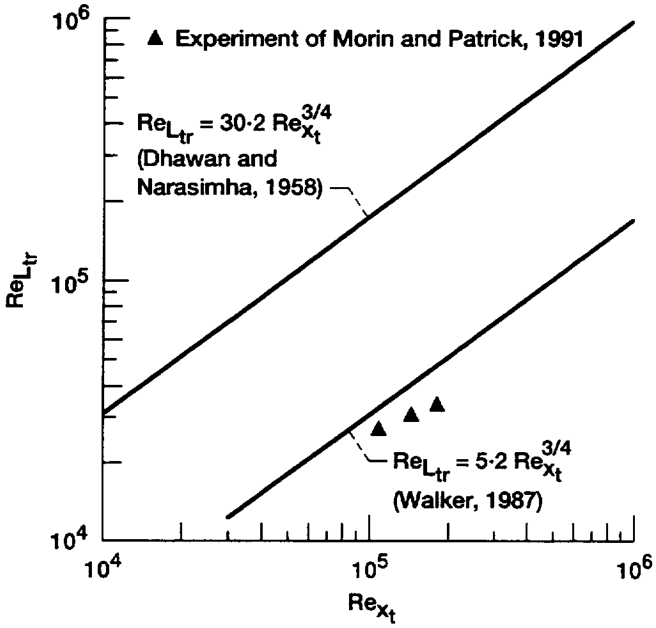

Figure 24.—Measured transition length of a separated laminar shear layer compared to flat-plate transition length and minimum possible transition length.

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

The progress in modeling of transition on turbine vanes and blades performed under the sponsorship of NASA Lewis Research Center is reviewed. Past work in bypass transition modeling for accurate heat transfer predictions, show that transition onset can be reasonably predicted by modified k - ε models, but fall short of predicting transition length. Improvements in the predictions of the transition region itself were made with intermittency models based on turbulent spot dynamics. Needs and proposals for extending the modeling to include wake passing and separation effects are outlined.

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