NASA TM- 86880

NASA Technical Memorandum 86880

A Review and Analysis of Boundary Layer Transition Data for Turbine Application

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Prepared for the
Thirtieth International Gas Turbine Conference and Exhibit
sponsored by the American Society of Mechanical Engineers
Houston, Texas, March 17-21, 1985

A REVIEW AND ANALYSIS OF BOUNDARY LAYER TRANSITION DATA FOR TURBINE APPLICATION

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ABSTRACT

A Symposium on Transition in Turbines was held recently at the NASA Lewis Research Center. One recommendation of the working groups was the collection of existing transition data to provide standard cases against which models could be tested. This paper represents a preliminary response to that recommendation.

A number of data sets from the open literature that include heat transfer data in apparently transitional boundary layers, with particular application to the turbine environment, were reviewed and analyzed to extract transition information from the heat transfer data. The data were analyzed using a version of the STAN5 two-dimensional boundary layer code. The transition starting and ending points were determined by adjusting parameters in STAN5 until the calculations matched the data. The results are presented as tables of the deduced transition location and length as functions of the test parameters. The data sets reviewed cover a wide range of flow conditions, from low speed, flat plate tests to full scale turbine airfoils operating at simulated turbine engine conditions. The results indicate that free stream turbulence and pressure gradient have strong, and opposite, effects on the location of the start of transition and on the length of the transition zone.

INTRODUCTION

A Symposium on Transition in Turbines was held recently at the NASA Lewis Research Center. One recommendation of the working groups was the collection of existing transition data to provide standard cases against which models could be tested. This paper represents a preliminary response to that recommendation.

The design of efficient cooling configurations for the airfoils in a gas turbine engine requires a detailed knowledge of the variations of the heat transfer coefficient on the hot gas side. However, in many cases, there is a region on the blade surface where the heat transfer coefficient experiences a dramatic rise in magnitude. This is the region where the boundary layer transition from laminar to turbulent flow occurs. The location of the start of this transition, and the length of the transition zone, depend strongly on a number of flow parameters, such as the Reynolds number, the free stream turbulence level and the pressure gradient.

The computation of the heat transfer coefficient in the transition region requires that a mathematical model be used to smoothly turn-on the turbulent calculations. At the present time there is no model available that adequately accounts for the effects of the above parameters in the turbine environment. One of the reasons for this is a lack of good experimental data on boundary layer transition under the severe conditions encountered in a gas turbine engine. However, a number of heat transfer data sets do exist that include transitional boundary layers. In this study, these data sets were analyzed using the STAN5 two-dimensional boundary layer computer code in order to extract transition information from the heat transfer data. The code was run against the data with different transition parameters assumed until a match between data and calculations was found. This transition data was then tabulated in a form useful to the researcher attempting to model the transition process in the turbine environment.

METHOD OF ANALYSIS

An iterative method was used to derive transition data from the selected heat transfer data sets. The general procedure was to assume a transition starting point and a transition length, do a numerical boundary layer analysis to compute heat transfer parameters, and, finally, compare the computed results to the data. If the agreement was poor, new transition points were assumed, and the process was repeated until reasonable agreement was found between computed and measured results. The final values of transition starting point and transition zone length are what are reported here, in terms of location as well as momentum thickness Reynolds number.

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The boundary layer analysis used was the widely accepted STAN5 two-dimensional boundary layer code, developed at Stanford University by Crawford and Kays (1), based on the scheme of Patankar and Spalding (2). The version of STAN5 used has been modified at the NASA Lewis Research Center by Gaugler (3). In this version, the user has the option of supplying the program with a specific location where transition is to start, and with a specific length of the transition region. Within the transition zone, the turbulent eddy viscosity is gradually turned on, using an intermittency factor variation taken from the work of Abu-Ghannam and Shaw (4).

The intermittency factor varies smoothly from zero at the transition start point to one at the end of the specified transition length. No attempt was made to account for local effects such as pressure gradient or free stream turbulence in the computation of intermittency.

The Prandtl mixing length model was used to compute the turbulent eddy diffusivity.

SELECTION OF DATASETS

A number of heat transfer datasets were reviewed for their applicability to this report. From these, six datasets were selected for analysis. The prime criterion used in the selection process was that the data show evidence of boundary layer transition. When this was met, the completeness of the documentation of the experimental conditions became the prime criteria. As a minimum, in order to do the boundary layer analysis, the aerodynamic and thermal boundary conditions must be known, including the specification of free stream turbulence parameters.

A description of each of the selected datasets follows and is summarized in Table I.

1. The first data considered were extracted from the report by Blair and Werle (5). Their tests considered incompressible flow over a heated, smooth flat plate, for different levels of free stream turbulence. They were primarily looking for the effects of free stream turbulence level on heat transfer to the fully turbulent boundary layer, but they did allow the boundary layer to undergo a natural transition from laminar to turbulent. Two of their test runs were selected for this analysis, and the conditions are summarized in Table I, identified as Cases 1(a) and (b). The only difference between the two is the free stream turbulence level. The inlet Reynolds number is based on the test section length, 8.0 ft (2.44 m).

2. The second set of data used was taken from another report by Blair and Werle (6) and by Blair (7). The tests described were very similar to the first set, but with the addition of a constant flow acceleration. Three of these test runs were selected for analysis, encompassing two different pressure gradients and two different turbulence levels. The pertinent test parameters are summarized in Table I, labeled as Cases 2(a), (b), and (c). Again, the inlet Reynolds number is based on the test section length, 8.0 ft (2.44 m).

3. The third dataset was taken from the work of Han et al. (8). They measured the heat transfer from three different large scale turbine airfoils over a range of Reynolds numbers and free stream turbulence levels. The airfoils had a true chord of 21 in (53.3 cm) and a height of 24 in (61 cm). One of these datasets, for an airfoil suction (convex) surface, was selected for analysis in this study, and the test parameters are summarized in Table I, labeled as Case 3. For this case, and those remaining, the inlet Reynolds number is based on airfoil true chord. The dataset from (8) is for incompressible flow, as the test used ambient air flowing over an electrically heated airfoil.

4. The fourth dataset considered was extracted from the report by Consigny and Richards (9). They used the isentropic light-piston tunnel at Von Karman Institute to closely simulate actual turbine engine conditions and measured the heat transfer rates to the model airfoil. The airfoil had a true chord of 3.15 in (8.0 cm) and a height of 3.94 in (10 cm). Information from two of their runs was used for this report, and the conditions are tabulated in Table I as Cases 4(a) and (b). The runs selected differed only in the initial free stream turbulence level. Again, only the suction surface data was considered here. For these cases, the air was hotter than the surface.

5. The fifth dataset was taken from the report of Schultz et al. (10), and from additional information reported by Daniels and Browne (11). The facility used was the free-piston tunnel at Oxford University, using techniques similar to those in Case 4 to measure heat transfer rates to a turbine airfoil. The airfoil had a true chord of 1.96 in (5.0 cm) and a height of 2.96 in (7.5 cm). The two cases described in (10) and (11) were both used here, and the conditions are tabulated in Table I as Cases 5(a) and (b). As in the previous cases, only suction surface data was considered for this analysis. The only difference between Cases 5(a) and (b) is the inlet Reynolds number.

6. The final dataset considered for this report was taken from the suction surface data reported by Lander (12) and Lander et al. (13). This data was generated in a transient test using hot combustion gases to heat a cascade of turbine airfoils that was quickly shuttled into the hot stream. The airfoils had a true chord of 2.36 in (6.0 cm) and a height of 2.3 in (5.8 cm). The reported tests were characterized by extremely high free stream turbulence levels. The conditions of the case used here are tabulated in Table I as Case 6.

RESULTS AND DISCUSSION

Comparison plots of the results of this analysis are presented in Figs. 1 to 6, and important parameters are tabulated in Table II. The plots show either Stanton number or heat transfer coefficient as functions of the surface distance from the stagnation point. The two parameters most frequently found in the literature to govern the boundary layer transition are free stream pressure gradient and turbulence level, with the favorable pressure gradient associated with streamwise acceleration having a stabilizing effect and free stream turbulence acting to trigger instabilities. For the cases studied here, these two parameters are tabulated in Table II and are included on the figures. The turbulence level is defined as the ratio of the root mean square of the streamwise fluctuating velocity, u, to the free stream velocity, U. The pressure gradient is characterized by the acceleration parameter, K, defined as the product of the kinematic viscosity, ν, and the streamwise velocity gradient, dU/dx, divided by the square of the free stream velocity.

$$K = \frac{\nu}{U^2}\frac{dU}{dx}$$

Included in Table II are the derived values of momentum thickness Reynolds number at the start and at the end of transition. The momentum thickness Reynolds number at the start of transition is the parameter calculated in most attempts to model the start of transition.

In all cases, the figures include curves for two additional STAN5 calculations, one where the boundary layer was assumed to remain laminar and one where it was assumed fully turbulent from the start. These two cases form the limits between which the transitional calculations fall. In general, the laminar calculations matched the laminar data quite well and the fully turbulent calculations acceptably matched the turbulent data.

For the turbulent case, the Prandtl mixing length model was used to compute the turbulent eddy diffusivity.

Case 1. Figures 1(a) and (b) show the comparisons between the predicted Stanton number distribution and the measured distributions as reported in (5). The two cases, 1(a) and (b), differ only in the inlet free stream turbulence level. As expected, the data show that higher free stream turbulence results in earlier transition, as well as a shorter transition length. The results of the analysis are summarized in Table II. Note that the best fit occurs when transition is assumed to start very close to the point of minimum measured heat transfer. This was not true for the cases that include pressure gradient effects.

Case 2. The datasets for Case 2 have the added complication of an accelerating free stream flow. The comparisons of data and calculations are shown in Figs. 2(a), (b), and (c). For reference purposes, the free stream velocity distribution is included on Fig. 2, and all subsequent figures. An interesting feature of the calculations is that in order to match the data, the transition starting point must be located condiderably ahead of the minimum heat transfer point. The largest effect of acceleration is seen in comparing Figs. 2(a) and (b) which are for about the same turbulence level. The higher acceleration of Case 2(b) results in a considerably lengthened transition zone compared to Case 2(a). A comparison of Figs. 2(b) and (c) shows that for constant free stream acceleration parameter, free stream turbulence has a very strong effect on the length of the transition zone, with the more turbulent Case 2(c) having a very short transition region.

Case 3. Figure 3 shows the results for Case 3. This case represents flow over an actual airfoil, so flow accelerations are not constant, and surface curvature effects are also present. However, free stream turbulence level is relatively low. From Fig. 3 it is seen that transition must be forced to start in a region where the flow acceleration is high, well ahead of the minimum heat transfer point, in order to match the behavior of the data.

Case 4. Figures 4(a) and (b) show the results for Case 4, a turbine vane suction surface. Essentially the only difference between the two cases was the free stream turbulence level. The distribution of flow acceleration parameter, K, over the airfoil surface was the same for both. In both cases, it was necessary to force transition in the calculations to begin very close to the leading edge stagnation point, but the length of the transition zone is markedly different. For the lower turbulence case, (Fig. 4(a)), the calculated boundary layer never reached a fully turbulent state. The agreement between the STAN5 laminar and turbulent calculations and the data was significantly worse for the higher turbulence case.

Case 5. Figures 5(a) and (b) compare two cases where the only difference between the experiments was the Reynolds number, which, since the velocity distributions were the same, resulted in a different level of acceleration parameter. Figure 5(b) results were for a test run with an inlet Reynolds number of 1.26 million, three times the value for the results shown in Fig. 5(a). Major differences are apparent in the transitional boundary layer heat transfer data. The most obvious reason for this would appear to be the effect of the acceleration parameter, K, which, for a constant velocity, varies inversly with the Reynolds number. Thus, the longer transition zone for the low Reynolds number case, since the stabilizing parameter, K, is higher.

Case 6. Figure 6 shows the result of analyzing Case 6. The distinguishing feature of this dataset is the very high inlet turbulence level. However, the effect of the free stream turbulence is offset by a very strongly accelerating flow for about the first 15 percent of the vane surface. Once the flow acceleration diminishes, the transition progresses very rapidly.

SUMMARY AND CONCLUSIONS

A number of heat transfer datasets were analyzed to determine the location of the start of boundary layer transition from laminar to turbulent flow and the length of the transition zone. The analysis used was the STAN5 two-dimensional boundary layer program. Transition starting point and the length of the transition zone were adjusted in the program input until the calculated heat transfer distribution matched the measured distribution to a satisfactory extent. From this analysis, the momentum thickness Reynolds number at the start and end of transition was determined, and the results were tabulated as a function of experimental conditions. The location of the start of boundary layer transition was seen to exhibit a strong dependence on both free stream pressure gradient and turbulence level. Favorable pressure gradient tends to delay the onset of turbulent flow, which is opposite to the effect of free stream turbulence, which tends to hasten the transition. The length of the transition zone appears to depend strongly on free stream parameters within the zone rather than just on the conditions at the beginning of transition, as is frequently assumed.

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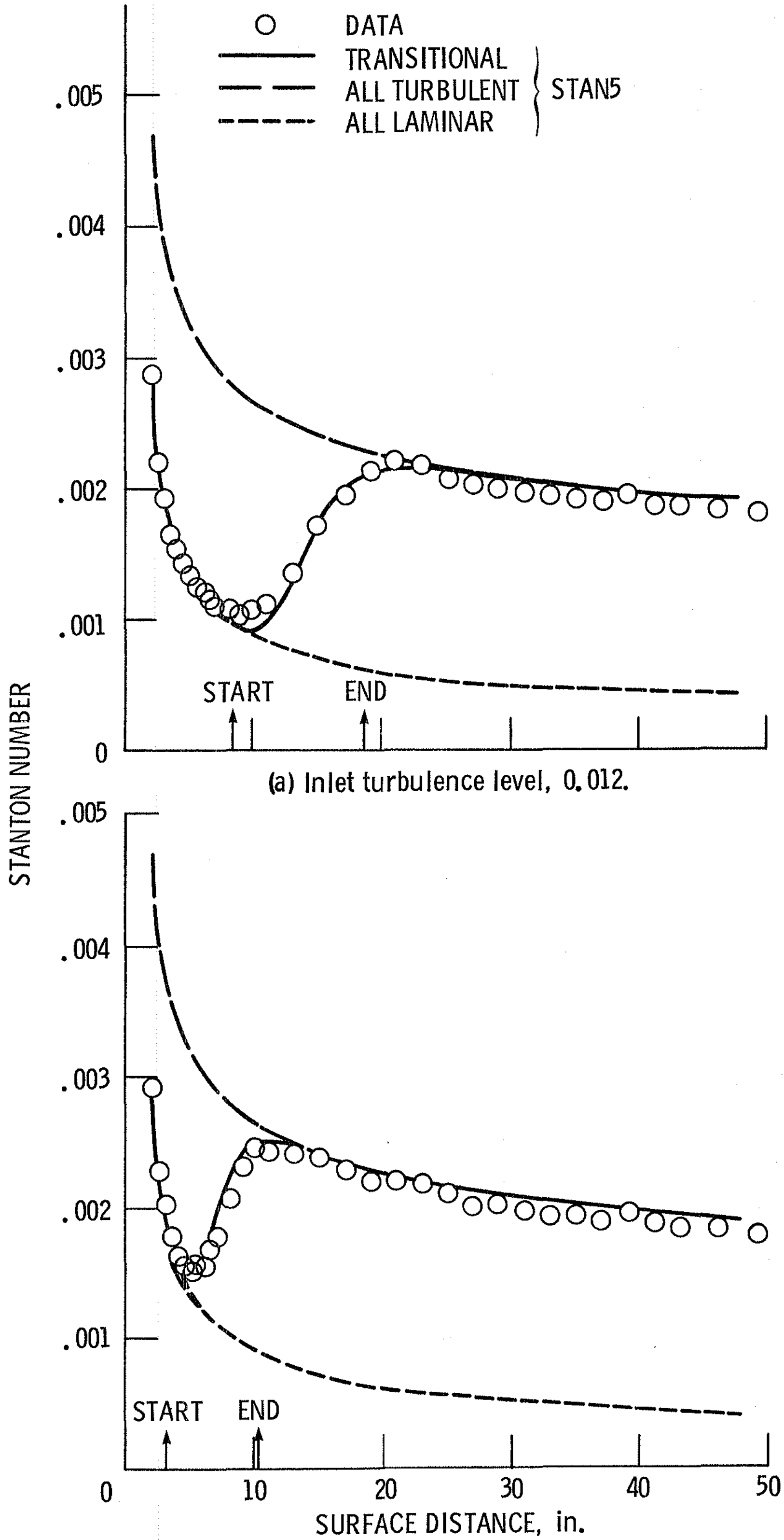
TABLE I. - COMPARISON OF EXPERIMENTAL CONDITIONS FOR THE SELECTED DATASETS

Case and figure	Reference	Test conditions	Inlet				Exit
			Wall to gas temperature ratio	Reynold's number $x10^{-5}$	Streamwise turbulence intensity	Pressure, atm	Mach number
1(a)	Blair and Werle (5)	Heated flat plate,	1.02	47.3	0.012	1.0	0.09
1(b)	Blair and Werle (5)	no acceleration, low speed	1.02	47.3	.025	1.0	.09
2(a)	Blair and Werle (6) and	Heated flat plate,	1.02	24.1	.021	1.0	.07
2(b)	Blair (7)	constant acceleration,	1.02	15.1	.023	1.0	.12
2(c)		low speed	1.02	15.1	.053	1.0	.12
3	Han et al. (8)	Heated large scale, airfoil, low speed	1.09	2.33	.008	1.0	.04
4(a)	Consigny and Richards (9)	Short duration test,	.76	7.23	.030	2.33	.92
4(b)		high speed	.76		.052	2.33	.92
5(a)	Shultz et al. (10) and	Short duration test,	.68	4.2	.040	1.88	.94
5(b)	Daniels and Brown (11)	high speed	.68	12.6	.040	5.75	.94
6	Lander (12)	Transient test, combustion heated	.53	3.75	.187	2.7	.85

TABLE II. - DERIVED TRANSISTION PARAMETERS

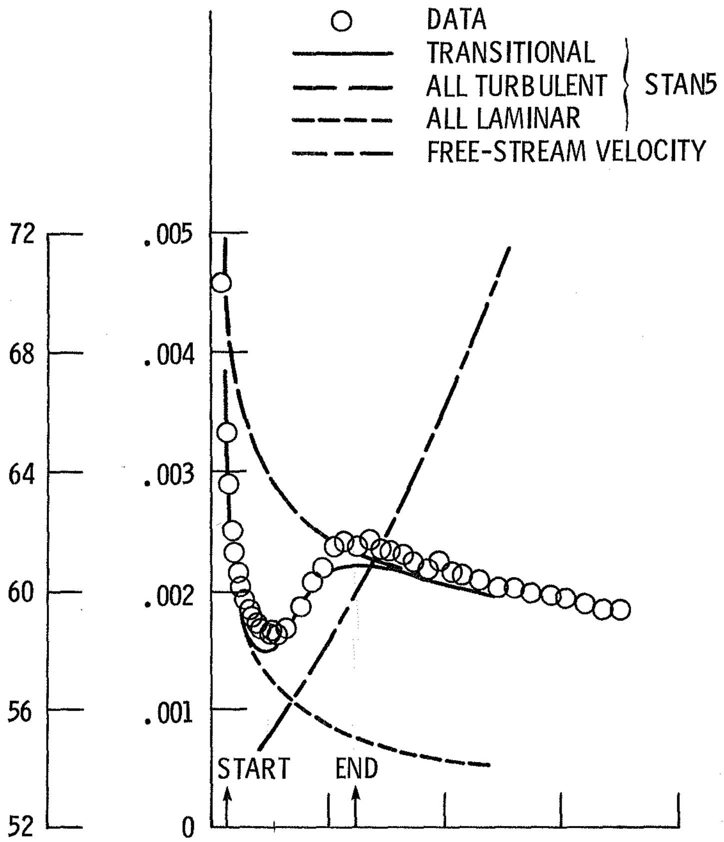
Case and figure	Local parameters at start of transition				End of transition	
	Assumed transition starting point, ft	Acceleration parameter $Kx10^{6}$	Streamwise turbulence intensity	Momentum thickness Reynolds number	Assumed length of transition zone, ft	Momentum thickness Reynolds number
1(a)	0.70	0	0.012	400	0.86	985
1(b)	.25	0	.025	260	.60	730
2(a)	.20	0.2	.021	165	1.85	895
2(b)	.14	.75	.023	92	5.00	975
2(c)	.10	.75	.053	92	0.80	330
3	.32	3.9	.005	150	1.19	1355
4(a)	.01	11.0	.030	74	(a)	(a)
4(b)	.01	11.0	.052	74	0.20	1440
5(a)	.03	2.1	.030	192	.125	1325
5(b)	.005	.88	.035	114	.065	1620
6	.005	120	.187	28	.10	688

aTransition not complete at end of vane surface.

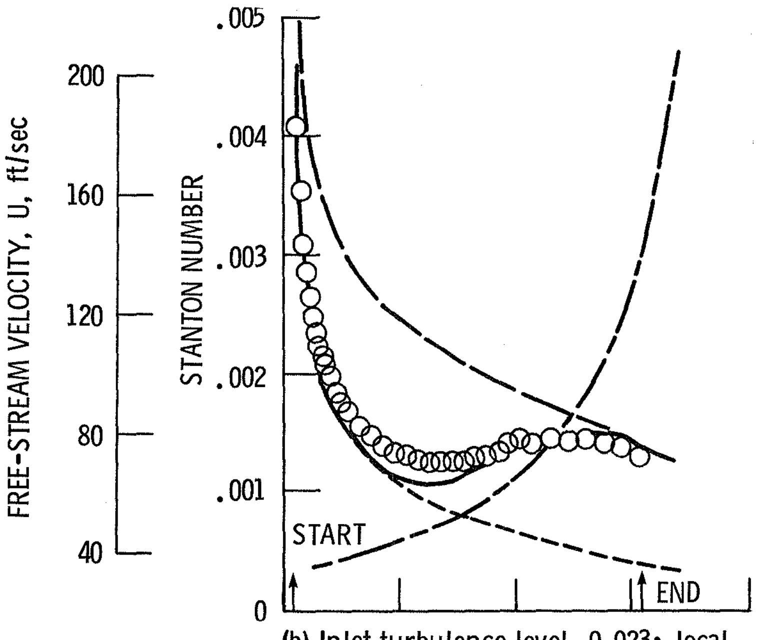


(b) Inlet turbulence level, 0.025.

Figure 1. - Stanton number as a function of surface distance. Flat plate; free-stream velocity, 100 ft/sec; data from Blair and Werle (5).

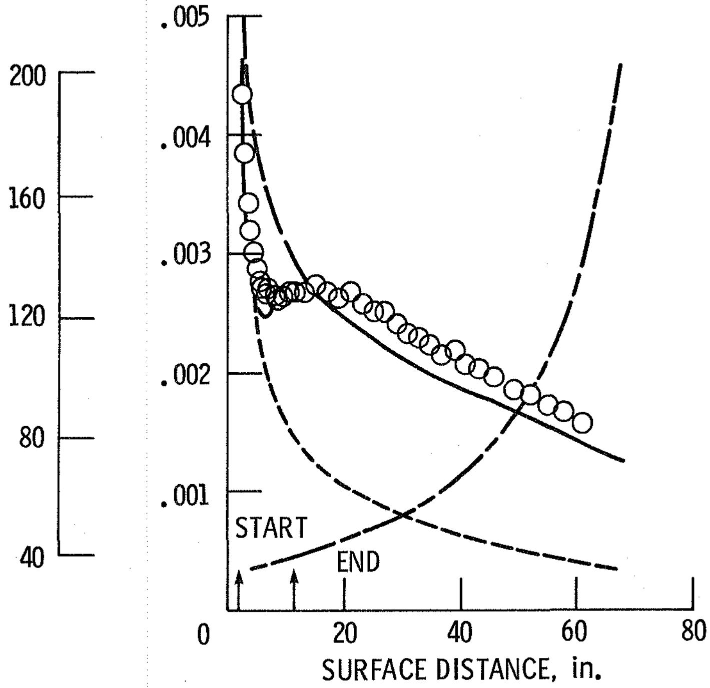


(a) Inlet turbulence level, 0.021; local acceleration parameter, K, 0.2×10^{-6}.



(b) Inlet turbulence level, 0.023; local acceleration parameter, K, 0.75×10^{-6}.

Figure 2. - Stanton number as a function of surface distance. Flat plate; constant acceleration; data from Blair and Werle (6).



(c) Inlet turbulence level, 0.053; local acceleration parameter, K, 0.75×10^{-6}.

Figure 2. - Concluded.

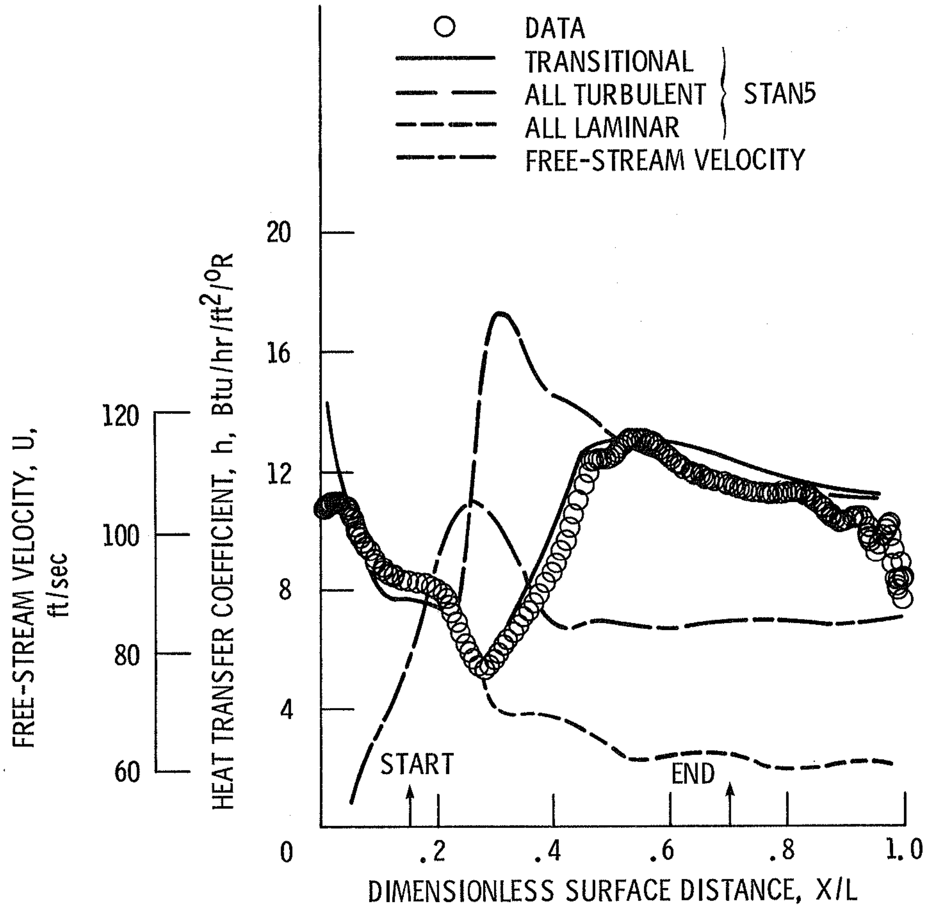


Figure 3. - Heat transfer coefficient as a function of surface distance. Large-scale turbine vane; suction surface; inlet turbulence level, 0.008; local acceleration parameter K at transition start, 0.39×10^{-5}. Data from Han et al. (8).

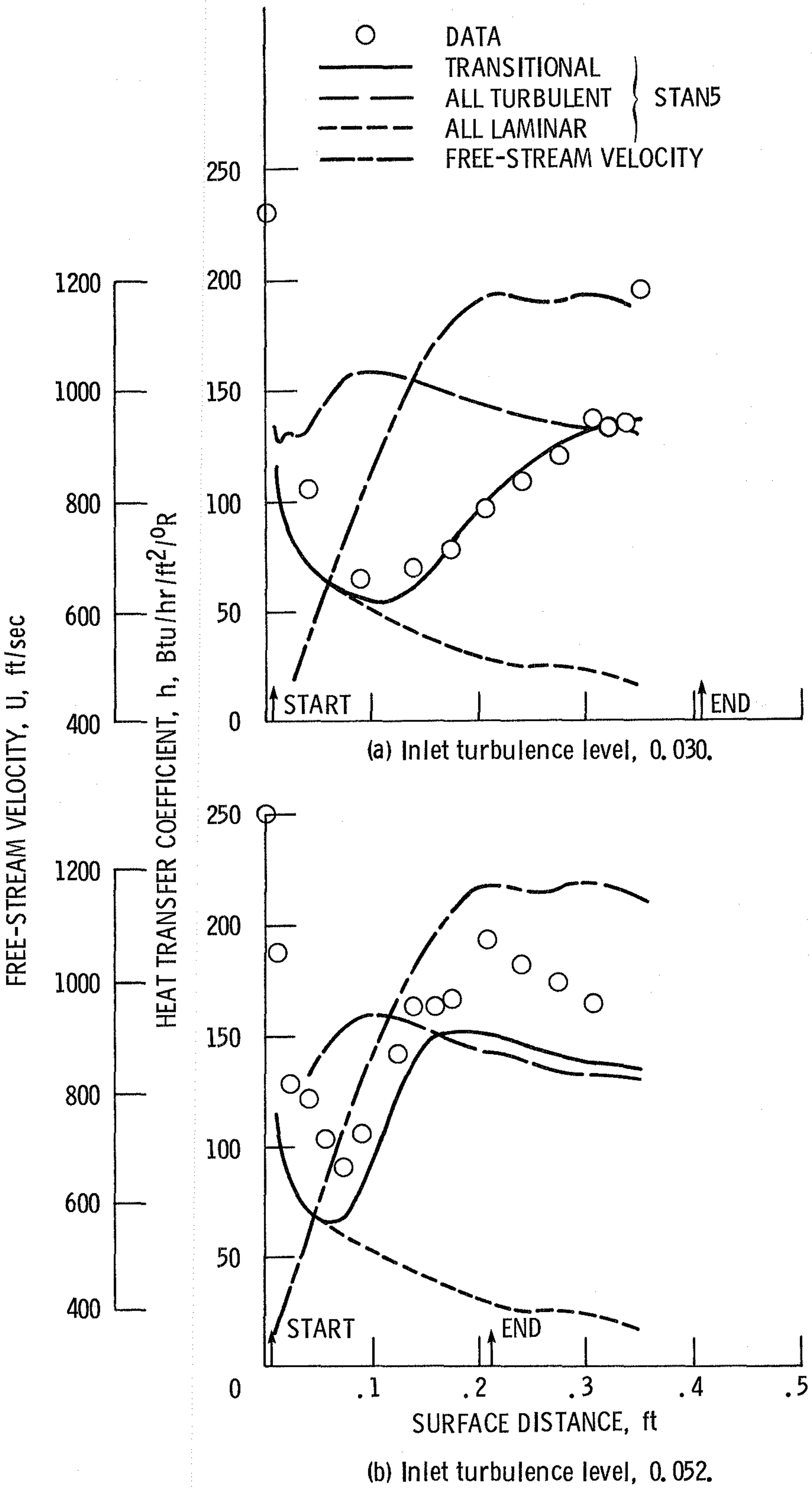


Figure 4. - Heat transfer coefficient as a function of surface distance. Turbine vane suction surface; simulated engine conditions; local acceleration parameter K at transition start, 0.11×10^{-4}. Data from Consigny and Richards (9).

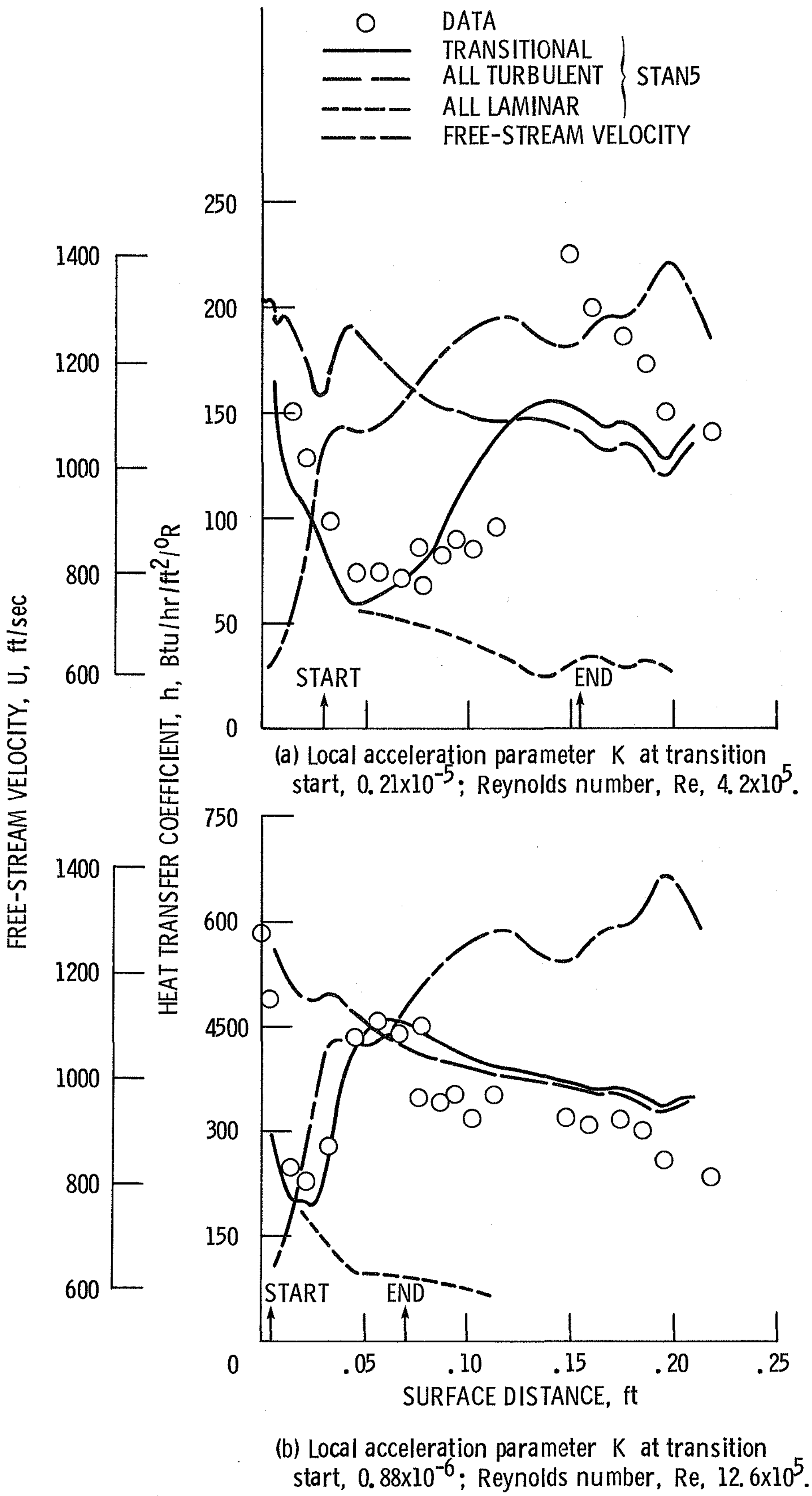


Figure 5. - Heat transfer coefficient as a function of surface length. Turbine vane suction surface; simulated engine conditions; inlet turbulence level, 0.040. Data from Shultz et al. (10).

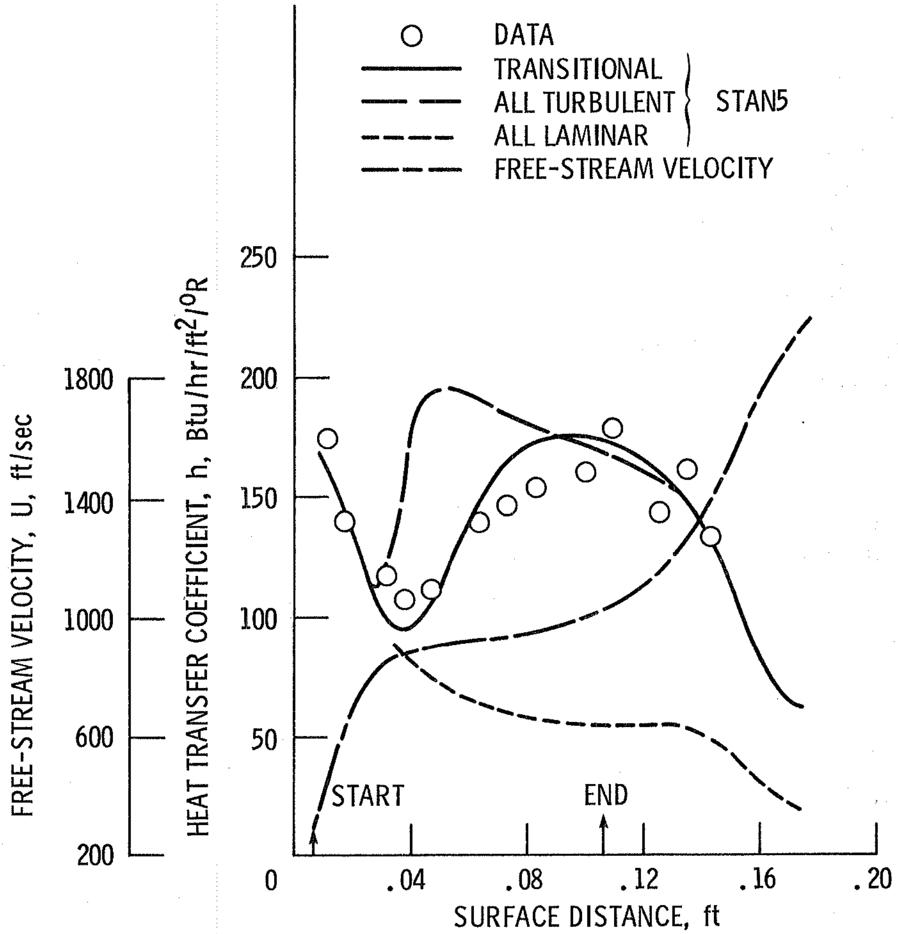


Figure 6. - Heat transfer coefficient as a function of surface length. Turbine vane suction surface; simulated engine conditions; inlet turbulence level, 0.187; local acceleration parameter K at transition start, 0.12×10^{-3}. Data from Lander (12), for very high turbulence.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-86880		
4. Title and Subtitle A Review and Analysis of Boundary Layer Transition Data for Turbine Application		5. Report Date 6. Performing Organization Code 505-31-04
7. Author(s) Raymond E. Gaugler		8. Performing Organization Report No. E-2341 10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administraion Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Thirtieth International Gas Turbine Conference and Exhibit sponsored by the American Society of Mechanical Engineers, Houston, Texas, March 17-21, 1985.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Boundary layer transition	Unclassified - unlimited STAR Category 34

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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