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

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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. The data were analyzed by 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 a table 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

Designing 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.

Computing the heat transfer coefficient in the transition region requires that a mathematical model be used to smoothly turn on the turbulent calculations. At present no model is available that adequately accounts for the effects of these 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 by using the STAN5 two-dimensional boundary layer computer code in order to extract transition information. The code was run against the data with different transition parameters assumed until a match between data and calculations was found. The transition data were then tabulated in a form useful to the researcher attempting to model the transition process in the turbine environment.

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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, to do a numerical boundary layer analysis to compute heat transfer parameters, and finally to compare the computed results with 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 reported herein, in terms of location as well as of momentum thickness Reynolds number.

The boundary layer analysis used was the widely accepted STAN5 two-dimensional boundary layer code, developed at Stanford University by Crawford and Kays (ref. 1) and based on the scheme of Patankar and Spalding (ref. 2). The version of STAN5 used has been modified at the NASA Lewis Research Center as described in reference 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 by using an intermittency factor variation taken from the work of Abu-Ghannam and Shaw (ref. 4). The intermittency factor varies smoothly from zero at the transition starting point to 1 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 computing intermittency. The Prandtl mixing length model was used to compute the turbulent eddy diffusivity.

SELECTION OF DATA SETS

A number of heat transfer data sets were reviewed for their applicability to this report. From these, six data sets 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 criterion. As a minimum, to do the boundary layer analysis, the aerodynamic and thermal boundary conditions must be known, including the specification of free-stream turbulence parameters.

Each of the selected data sets is described here and summarized in table I.

(1) The first data set was extracted from a report by Blair and Werle (ref. 5). Their tests concerned 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 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, 2.44 m (8.0 ft).

(2) The second data set used was taken from another report by Blair and Werle (ref. 6) and one by Blair (ref. 7). The tests were similar to the first set but with the addition of a constant flow acceleration. Three of these

test runs, encompassing two pressure gradients and two turbulence levels, were selected for analysis. The pertinent test parameters are summarized in table I as cases 2(a), (b), and (c). Again, the inlet Reynolds number is based on the test section length, 2.44 m (8.0 ft).

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

(4) The fourth data set considered was extracted from the report by Consigny and Richards (ref. 9). They used the isentropic light-piston tunnel at the 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 8.0 cm (3.15 in) and a height of 10 cm (3.94 in). 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 were considered herein. For these cases the air was hotter than the surface.

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

(6) The final data set considered for this report was taken from the suction surface data reported by Lander (ref. 12) and Lander et al. (ref. 13). These data were generated in a transient test by 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 6.0 cm (2.36 in) and a height of 5.8 cm (2.3 in). The reported tests were characterized by extremely high free-stream turbulence levels. The conditions of the case used herein are tabulated in table I as case 6.

RESULTS AND DISCUSSION

The results of this analysis are presented in figures 1 to 6, and important parameters are tabulated in table II. The figures 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: the favorable pressure gradient associated with streamwise acceleration has a stabilizing effect, and free-stream turbulence triggers instabilities. These two parameters are tabulated in table II for the cases studied herein 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 to be 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

The data for case 1 (fig. 1; table II) differed only in the inlet free-stream turbulence level. As expected, higher free-stream turbulence resulted in an earlier transition as well as a shorter transition length. The best fit occurred when transition was assumed to start close to the point of minimum measured heat transfer. This was not true for the cases that include pressure gradient effects.

Case 2

The data for case 2 (fig. 2; table II) had the added complication of an accelerating free-stream flow. For reference the free-stream velocity distribution is included on figure 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 considerably ahead of the minimum heat transfer point. The largest effect of acceleration is seen in comparing figures 2(a) and (b), which are for about the same turbulence level. The higher acceleration of case 2(b) resulted in a considerably longer transition zone than that for case 2(a). Comparing figures 2(b) and (c) shows that for a constant free-stream acceleration parameter free-stream turbulence had a strong effect on the length of the transition zone, with the more turbulent case 2(c) having a short transition region.

Case 3

Case 3 (fig. 3; table II) represents flow over an actual airfoil, so flow accelerations are not constant and surface curvature effects are present. However, the free-stream turbulence level is relatively low. The transition had to be forced in the calculations to start in a region where the flow acceleration was high, well ahead of the minimum heat transfer point, in order to match the behavior of the data.

Case 4

Case 4 (fig. 4; table II) was for a turbine vane suction surface. Essentially the only difference between the two cases was the free-stream turbulence level. The distribution of the flow acceleration parameter K over the airfoil surface was the same for both. In both cases it was necessary in the calculations to force transition to begin very close to the leading-edge stagnation point, but the length of the transition zone was markedly different in each case. For lower turbulence (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

The data for case 5 (fig. 5; table II) differed only in the Reynolds number. Since the velocity distributions were the same, this resulted in a different level of acceleration parameter. For an inlet Reynolds number of 1.26 million (case 5(b)), three times the value for case 5(a), major differences are apparent in the heat transfer data for the transitional boundary layer. The most obvious reason for this is the effect of K which, for a constant velocity, varies inversely with Reynolds number. Thus the transition zone was longer for the low-Reynolds-number case since the stabilizing parameter, K, was higher.

Case 6

The distinguishing feature of case 6 (fig. 6; table II) is the high inlet turbulence level. However, the effect of the free-stream turbulence was offset by a strongly accelerating flow for about the first 15 percent of the vane surface. Once the flow acceleration diminished, the transition progressed rapidly.

CONCLUDING REMARKS

A number of heat transfer data sets were analyzed to determine the location of the start of the 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. The transition starting point and the length of the transition zone were adjusted in the program input until the calculated heat transfer distribution satisfactorily matched the measured distribution. From this analysis the momentum thickness Reynolds numbers at the start and end of transition were determined, and the results were tabulated as a function of experimental conditions. The location of the start of the boundary layer transition exhibited a strong dependence on both free-stream pressure gradient and turbulence level. A favorable pressure gradient tended to delay the onset of turbulent flow, but the effect of free-stream turbulence was to hasten the transition. The length of the transition zone appeared to depend strongly on free-stream parameters within the zone rather than just on the conditions at the start of transition, as is frequently assumed.

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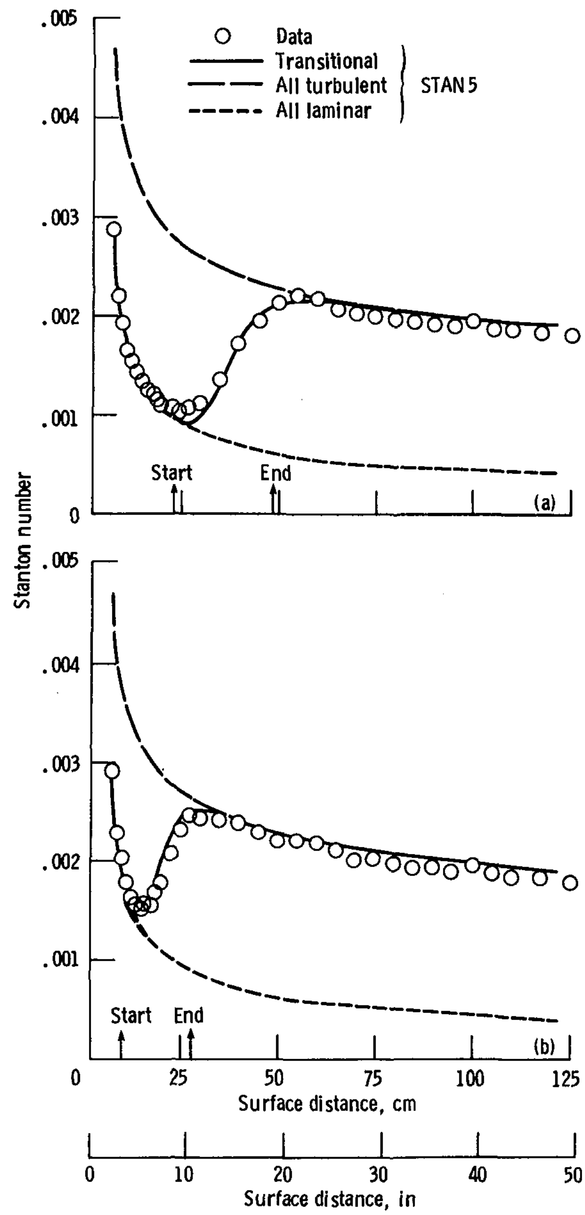
TABLE I. - EXPERIMENTAL CONDITIONS FOR SELECTED DATA SETS

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

TABLE II. - DERIVED LOCAL TRANSITION PARAMETERS

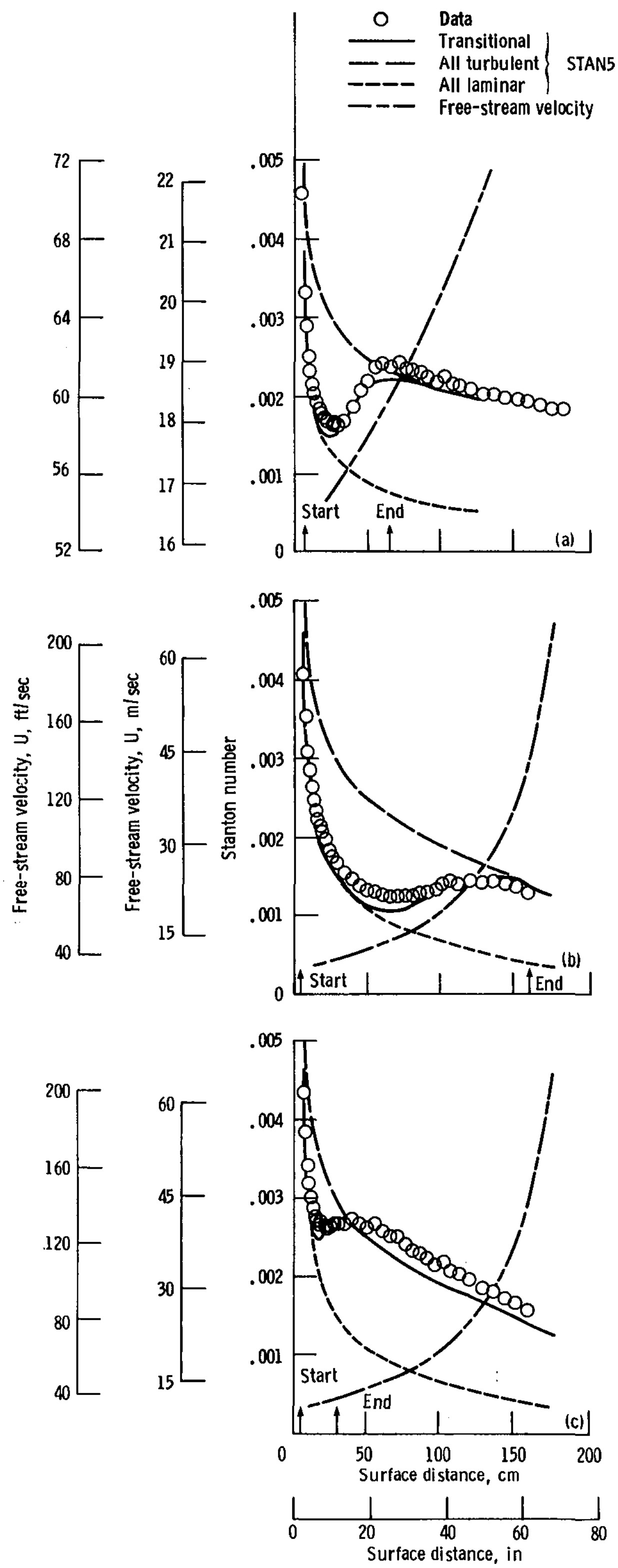
Case and figure	Start of transition					End of transition		
	Assumed transition starting point		Acceleration parameter, K	Streamwise turbulence intensity	Momentum thickness Reynolds number	Assumed length of transition zone		Momentum thickness Reynolds number
	m	ft				m	ft	
1(a)	0.213	0.70	0	0.012	400	0.262	0.86	985
1(b)	.076	.25	0	.025	260	.183	.60	730
2(a)	.061	.20	$.20x10^6$	.021	165	.564	1.85	895
2(b)	.043	.14	.75	.023	92	1.524	5.00	975
2(c)	.030	.10	.75	.053	92	.244	.80	330
3	.098	.32	3.9	.005	150	.363	1.19	1355
4(a)	.003	.01	11.0	.030	74	(a)	(a)	(a)
4(b)	.003	.01	11.0	.052	74	.061	.20	1440
5(a)	.009	.03	2.1	.030	192	.038	.125	1325
5(b)	.001	.005	.88	.035	114	.020	.065	1620
6	.001	.005	120	.187	28	.030	.10	688

[a]Transition not complete at end of vane surface.



(a) Inlet turbulence level, 0.012.
(b) Inlet turbulence level, 0.025.

Figure 1. - Stanton number as a function of surface distance. Flate plate; free-steam velocity, 30.5 m/sec (100 ft/sec). (Data from ref. 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}.
(c) Inlet turbulence level, 0.053; local acceleration parameter, K, 0.75×10^{-6}.

Figure 2. - Stanton number as a function of surface distance. Flat plate; constant acceleration. (Data from ref. 6).

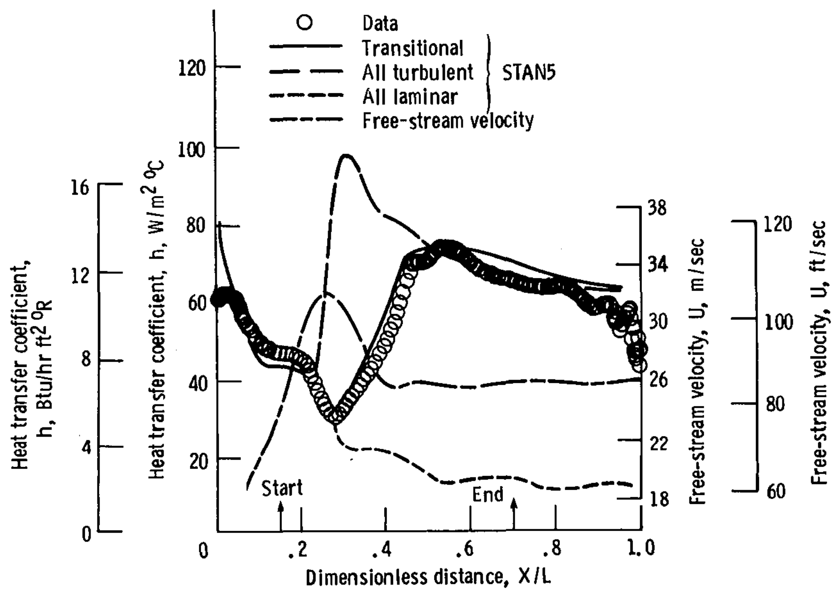
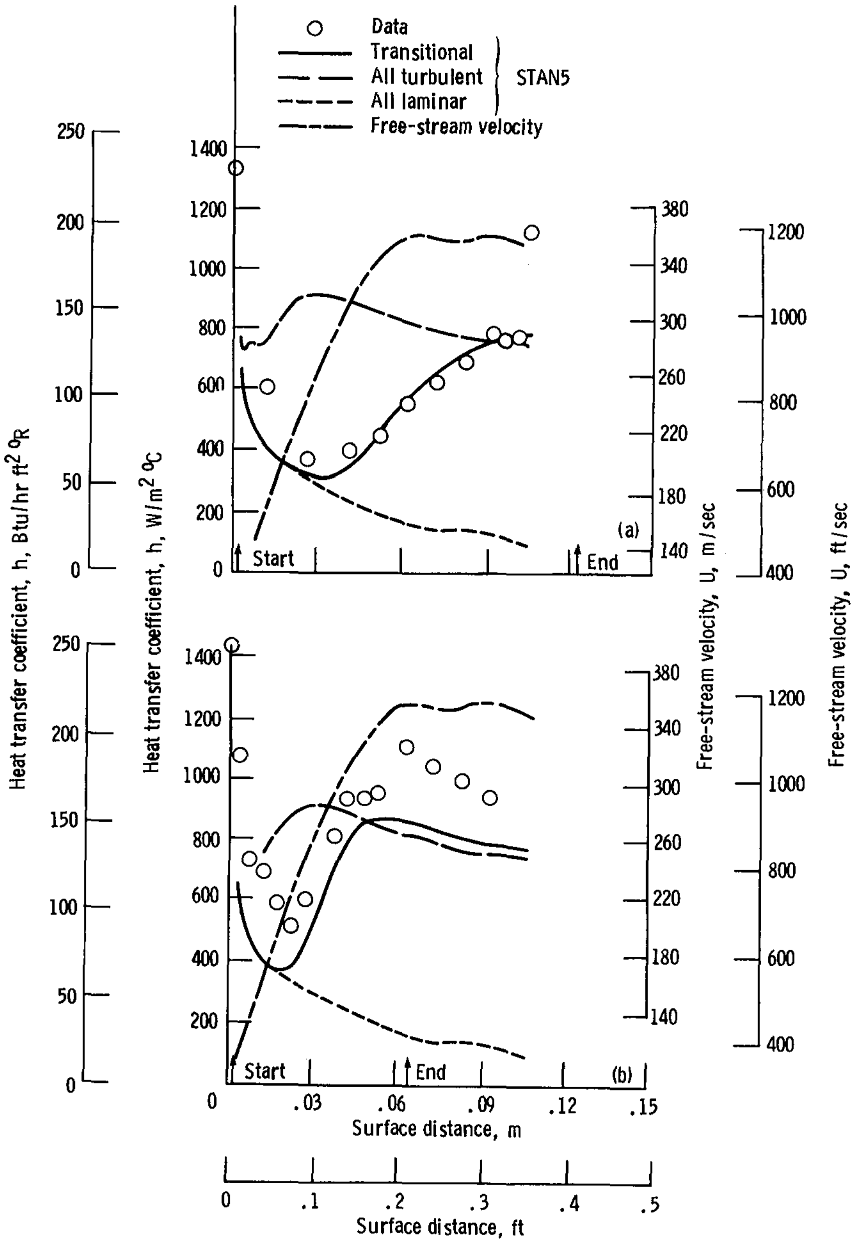
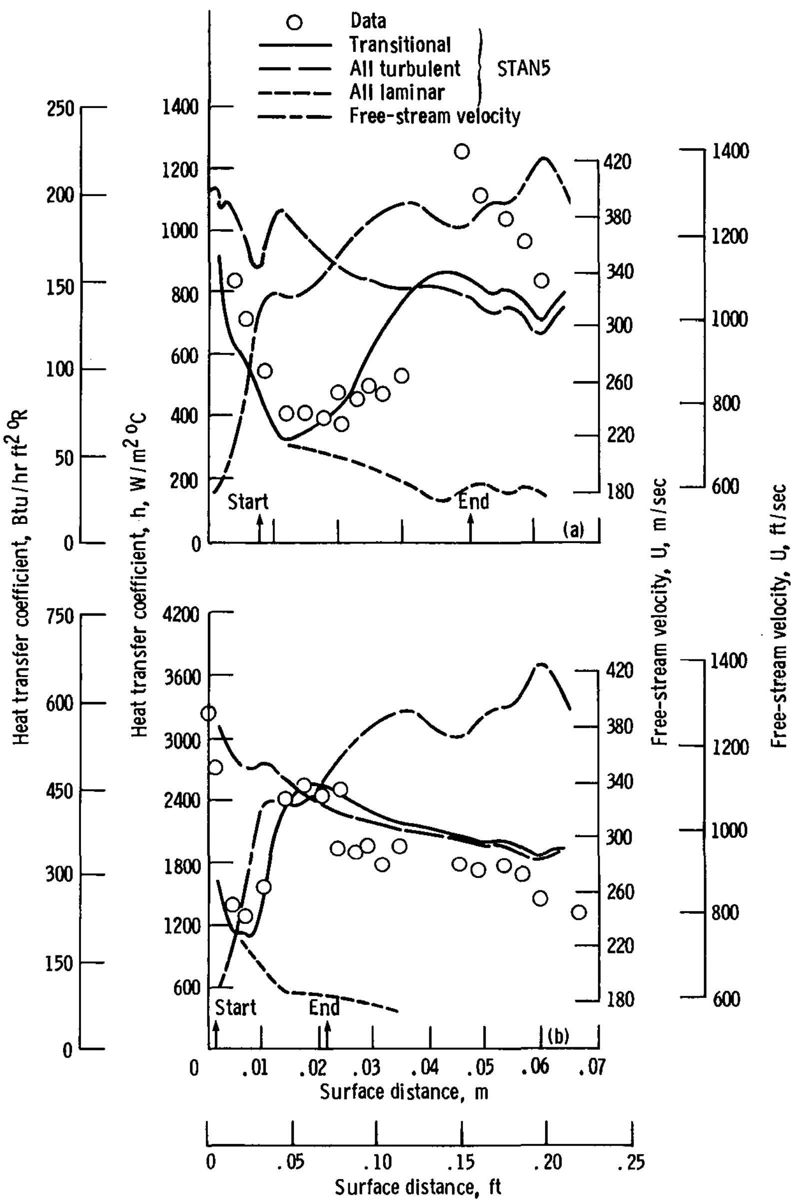


Figure 3. - Heat transfer coefficient as a function of surface distance. Large-scale turbine vane; suction surface; inlet turbulence level, 0.008; local acceleration parameter K at transition start, 0.39×10^{-5}. (Data from Han et al. (ref. 8).)



(a) Inlet turbulence level, 0.030.
(b) Inlet turbulence level, 0.052.

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 ref. 9.)



(a) Local acceleration parameter K at transition start, 0.21×10^{-5}; Reynolds number, Re, 4.2×10^{5}.

(b) Local acceleration parameter K at transition start, 0.88×10^{-6}; Reynolds number, Re, 12.6×10^{5}.

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

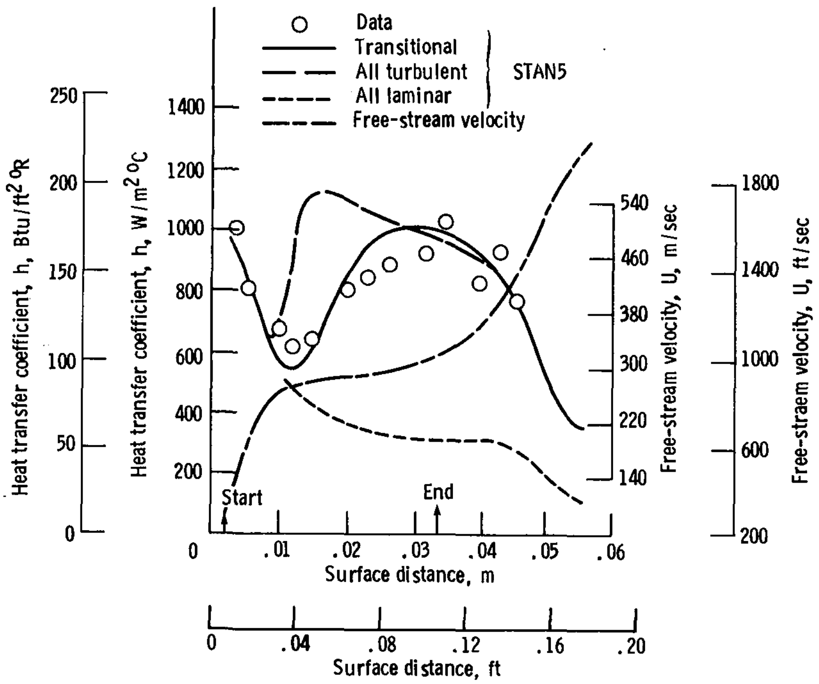


Figure 6. - Heat transfer coefficient as a function of surface distance. Turbine vane suction surface; simulated engine conditions; inlet turbulence level, 0.187; local acceleration parameter K at transition start, 0.12×10^{-3}. (Data from ref. 12 for very high turbulence.)