Comparison of Turbulent Prediction Methods with Ground and Flight Test Heating Data

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Nomenclature

F_{Re} = transformation function for Reynolds number
F_{St} = transformation function for Stanton number
$N_{Re,x}$ = Reynolds number based on wetted length
N_{St} = Stanton number

Subscript

i = incompressible

Theme

EXPERIMENTAL turbulent heating data and predictions usually are compared as a function of one test variable with others held constant. Data measured at different test conditions can be compared with predictions if the data are transformed to an incompressible plane according to the particular prediction method.[1] In this investigation, data obtained in both ground and flight tests for which the flow conditions are documented or are calculated readily are compared with results from several prediction methods in the respective incompressible planes. The purpose of this comparison is to provide simple engineering approaches for predicting turbulent boundary-layer heating. The results of this investigation[2] cover a wide range of experimental data and are unique since a direct comparison of flight and ground test results is possible.

Contents

The experimental turbulent heating data were obtained in ground and flight tests on flat plates and sharp or slightly blunted cones. The approximate range of local Mach numbers was from 1.4 to 15, and the approximate range of wall-total temperature ratios was from 1.3 to 0.1. The Reynolds number range varied according to whether the wetted length was computed from the beginning of transition (herein called the transition location) or from the peak heating point near the end of transition (herein called the peak heating point), but the approximate range was 1.0×10^6 to 3.0×10^8. The Reynolds numbers were based on a wetted distance rather than a momentum thickness since the momentum thickness is not available in many cases, especially on flight tests.

For cones, the local Stanton number was transformed to a flat plate, 0 deg angle-of-attack condition before applying a particular incompressible transformation. The "truncated" cone effect,[3] that is, the turbulent boundary layer beginning at a position other than the sharp tip, was included.

Since the accuracy of the data at any experimental condition is not known, a large number of data points were necessary to test the validity of the several methods. Although the data were not equally reliable, an estimate or an introduction of weighing factors has not been attempted. However, no experimental heating value for which the compressible Reynolds number based on distance from the peak heating point was less than 1.0×10^6 was used in the investigation.

The incompressible skin-friction relations used in the study[2] were those of Van Driest,[4] Spalding-Chi,[5,6] and Schultz-Grunow.[7] The local skin-friction equations were related to a Stanton number by a form of Reynolds analogy. The two modified forms of Reynolds analogy used for the study were Colburn[8] and Kármán.[9]

The experimental heating values and corresponding Reynolds numbers were transformed to an equivalent incompressible plane by using Van Driest II, Spalding-Chi, or Eckert reference-enthalpy transformations.[2] The data transformations are in a general form $N_{St,i} = F_{St} N_{St}$ and $N_{Re,x,i} = F_{Re} N_{Re,x}$, where F_{St} and F_{Re} are the incompressible transformations and are determined by comparison of the compressible and incompressible forms of the skin-friction relations.[2] The modified heating value then is compared to the respective incompressible relation.

Several error parameters were calculated for the study and were based on a percentage error between the modified experimental data and the analytic expressions. The mean, root mean square, and residual errors were computed for each comparison. Since equal confidence was placed upon all data points, the best "fit" of the experimental data by an analytical expression is defined in this study as the comparison with the minimum spread of the data about the analytic expression (minimum rms error).

The best overall agreement with all of the data (rms ≈ 15) is obtained with the Spalding-Chi and the Schultz-Grunow methods using the modified Colburn Reynolds analogy with the Reynolds number based on distance from the peak heating point for the Spalding-Chi method and on the distance from the transition location for the Schultz-Grunow method.

The flight data are approximately 15 to 25% higher than the wind-tunnel data at the same incompressible Reynolds number. The best agreement for the transformed wind-tunnel

Table 1 Error analysis for transformed data compared with the incompressible relations of Van Driest II, Spalding-Chi, and Schultz-Grunow

Reynolds number based on distance from peak heating point

Transformation method	Incompressible relation	Reynolds analogy	rms error: all data	rms error: wind-tunnel data	rms error: flight data
Van Driest II	Van Driest II	Colburn	23.06	26.25	13.93
		Kármán	18.52	20.01	14.61
Spalding-Chi	Spalding-Chi	Colburn	*14.93*	15.22	14.28
		Kármán	17.71	*14.44*	23.25
Eckert reference enthalpy	Schultz-Grunow	Colburn	19.62	20.93	16.46
		Kármán	17.66	16.72	19.53

Reynolds number based on distance from transition location

Transformation method	Incompressible relation	Reynolds analogy	rms error: all data	rms error: wind-tunnel data	rms error: flight data
Van Driest II	Van Driest II	Colburn	17.69	19.04	14.04
		Kármán	17.36	15.04	21.87
Spalding-Chi	Spalding-Chi	Colburn	17.25	15.65	20.52
		Kármán	25.66	21.04	34.11
Eckert reference enthalpy	Schultz-Grunow	Colburn	*14.65*	15.78	*11.66*
		Kármán	18.60	17.69	20.57

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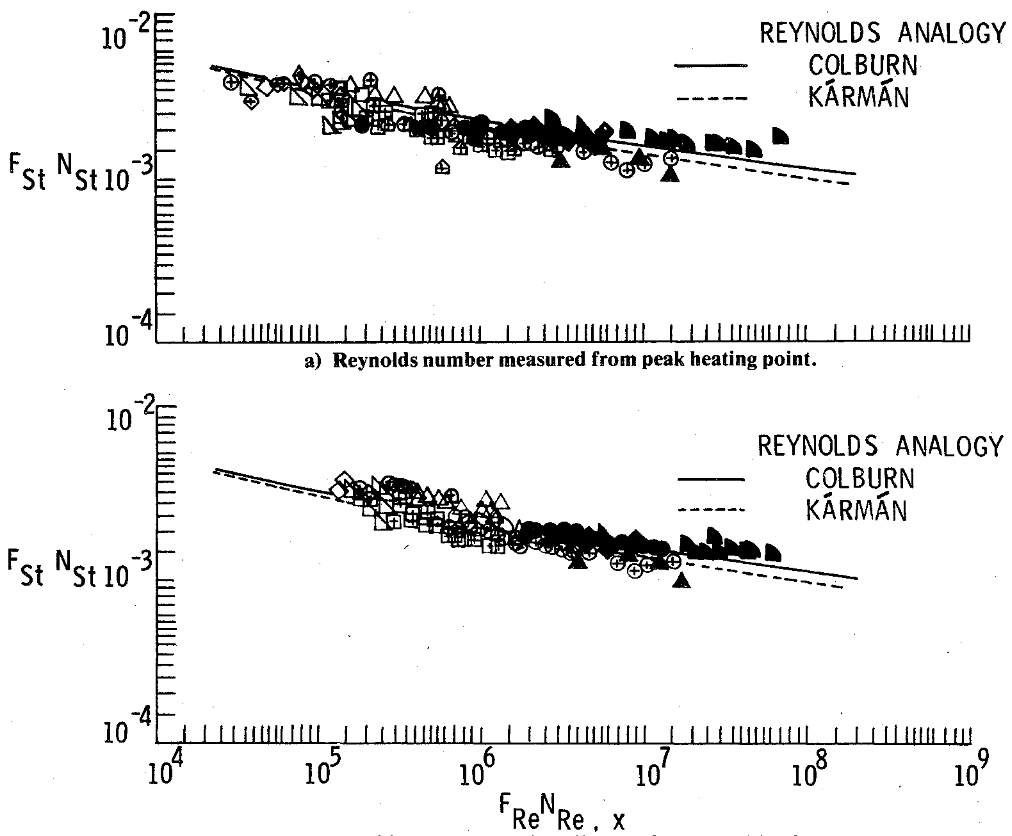

a) Reynolds number measured from peak heating point.

b) Reynolds number based on distance from transition location.

Fig. 1 Turbulent heat data transformed by the Eckert reference-enthalpy method and compared with the Schultz-Grunow relation.

data (rms = 14.44) was obtained with the Spalding-Chi method using the Kármán Reynolds analogy and Reynolds number based on distance from the peak heating point. The best agreement for the transformed flight test data (rms = 11.55) was obtained with the Schultz-Grunow method using the Colburn Reynolds analogy and the Reynolds number based on distance from the transition location. A summary of the important results in Ref. 2 is presented in Table 1. Also, a typical plot of the comparisons is shown in Fig. 1 where the turbulent heating data transformed by the Eckert reference-enthalpy method are compared with the incompressible Schultz-Grunow relation.

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