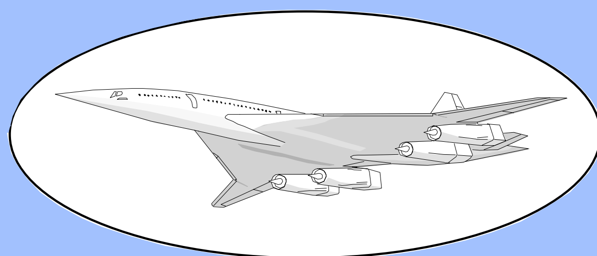
Assessment of CFD Predictions of Flat Plate Skin Friction



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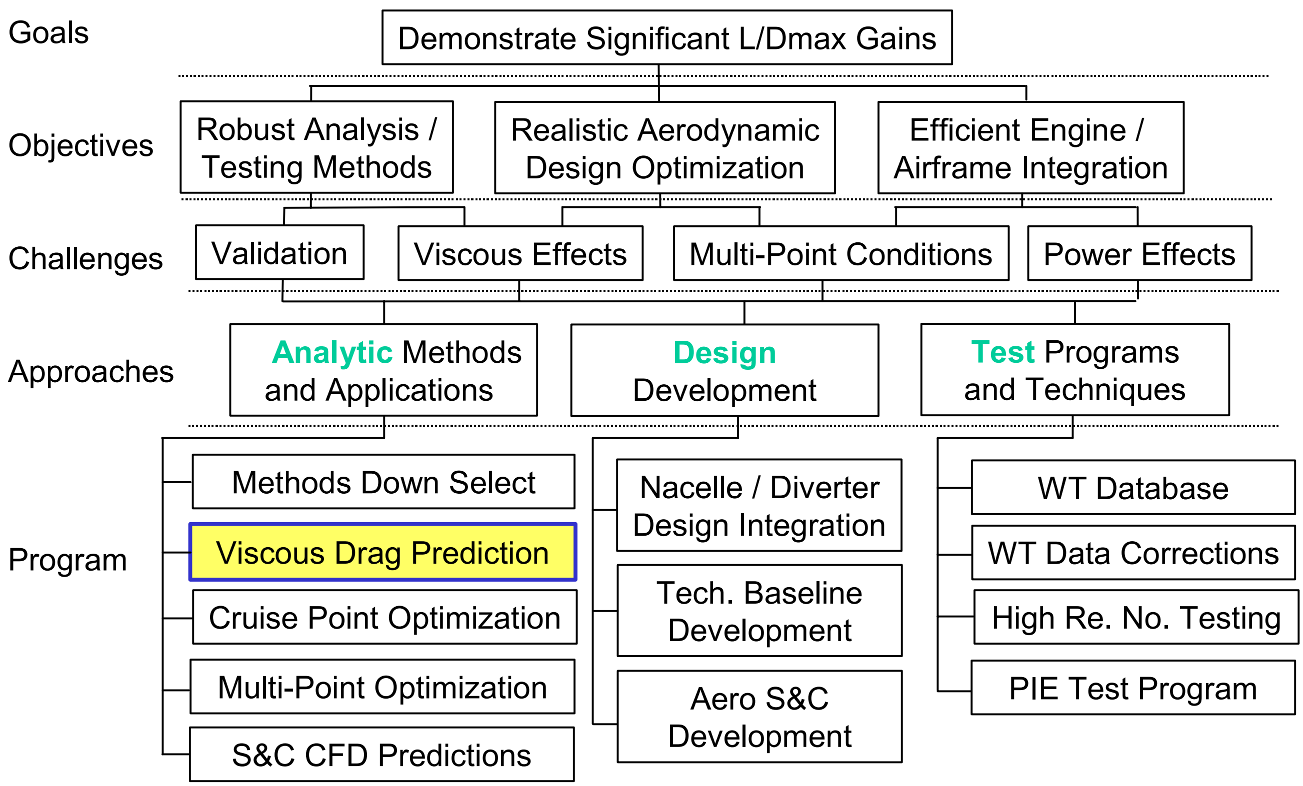
Configuration Aerodynamics Technology Development

Program Selects Best Analysis / Design Optimization Methods



The assessment of the CFD flat plate fully turbulent flow skin friction predictions is an element of the "Viscous Drag Prediction" technology development element shown in the Configuration Aerodynamics program on a page shown in this figure.

Topics

- Variations in Viscous Drag Predictions
- Resolution Strategy
- Flat Plate Skin Friction Comparison Database
- BLB-PW CFL3D Predictions
- BCA Overflow Predictions
- Ames OVERFLOW Predictions
- Conclusions

Recent CFD validation studies have shown significant variations in viscous drag predictions between the various methods used by the NASA and industry HSCT organizations. The methods include Navier Stokes CFD codes in which the viscous forces are part of the solutions, and predictions obtained from the different fully turbulent flow flat plate skin friction drag equations used by the various organizations.

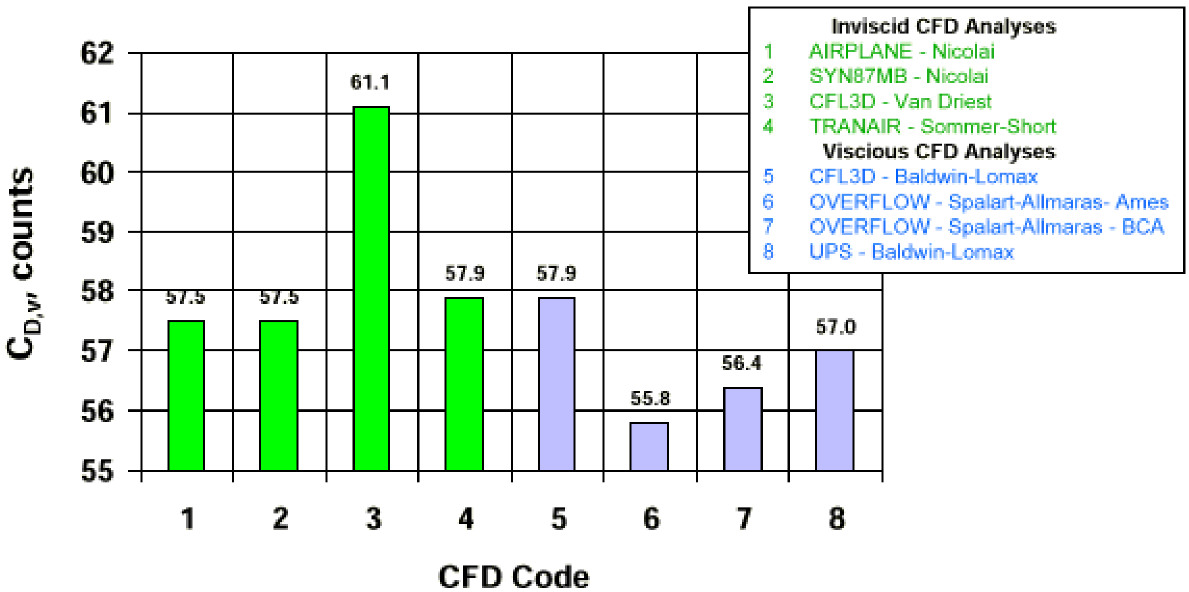
In this paper, the variation of these viscous drag predictions will be shown. The strategy developed to resolve these differences will be discussed. The first step in the resolution strategy was the development of a skin friction database for flat plate fully turbulent flow. This database will be briefly reviewed. The comparisons of CFD skin friction prediction by Boeing Phantom Works Long Beach, BPW-LB, by Boeing Commercial Aircraft aerodynamics, BCA, and by NASA Ames will be reviewed.

The BPW-LB CFD predictions were amde by Hamid Jafroudi of Alpha Star Corp, the BCA calculations were obtained by Max Kandula of Dynacs, and the NASA Ames calculations were made by Scott Lawrence

The study conclusions will be summarized.

Comparison of Predicted Viscous Drags From Various CFD Codes for the TCA Wing/Body Configuration

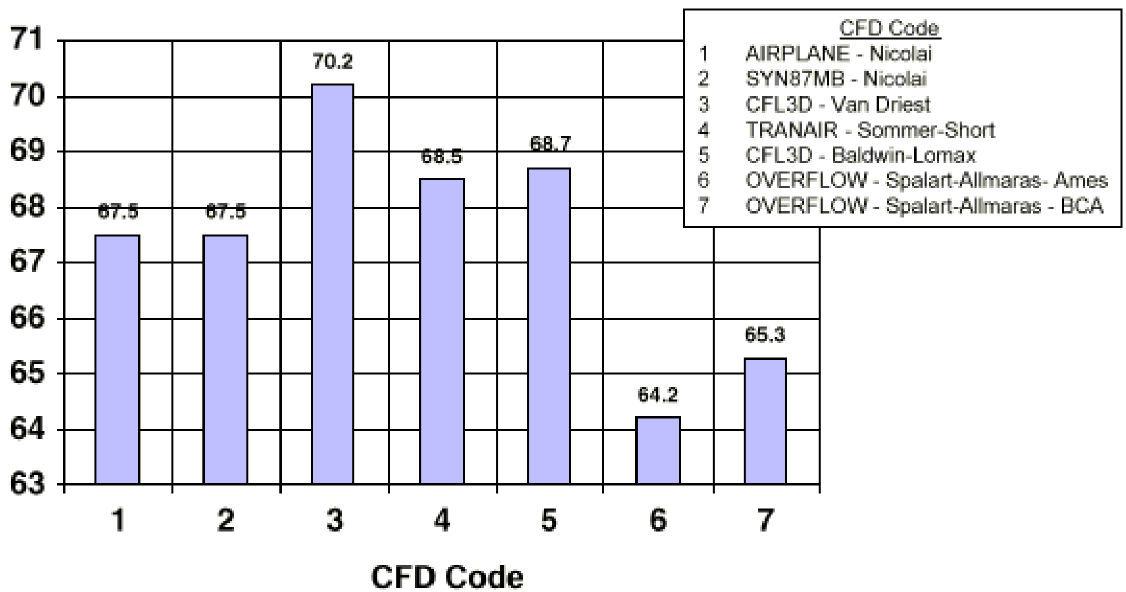
$M_\infty = 2.4$, $C_L = 0.1$, $R_e = 6.36 \times 10^6$



This figure illustrates the variations in viscous drag predictions for the TCA wind tunnel model wing plus body configuration. There are significant variations in flat plate theory predictions used in the inviscid CFD analyses as well as the CFD predictions obtained with the viscous analyses.

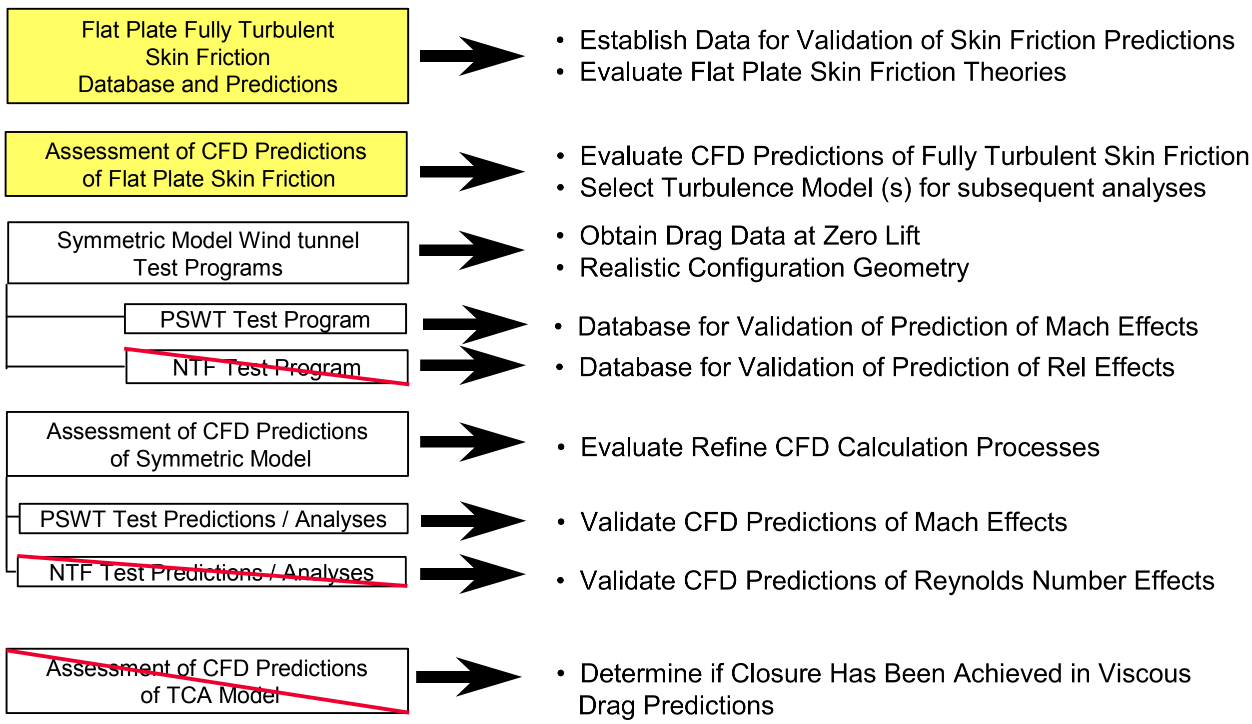
Comparison of Predicted Viscous Drags From Various CFD Codes for the TCA Wing/Body/Nacelle/Diverter Configuration

$M_\infty = 2.4$, $C_L = 0.1$, $R_e = 6.36\times10^6$



This figure shows similar comparisons for the wing plus body plus nacelle configuration. There is seen to be a three drag count variation in the flat plate predictions corresponding to the inviscid analyses, (numbers 1 through 4). The BLB-PW CFD predictions using CFL3D appear to match the flat plate theory predictions. The OVERFLOW predictions of BCA and Ames predict significantly lower drag levels.

Resolution Strategy



This illustrates the strategy that was developed to resolve the viscous drag prediction differences. This consisted of a series of sequential activities:

• Establish a database of fully turbulent flow flat plate skin friction data to be used for the validation of the corresponding CFD predictions. Flat plate prediction methods were assessed. A modified flat plate skin friction prediction method was developed that accurately represents the mean of the test data and captures both the Reynolds number and Mach number variations of this mean.

• The second step includes the comparison of the CFD predictions of fully turbulent flow flat plat viscous drag with the modified flat plate theory. The results of this activity is the subject of this paper.

• A symmetric model representation of the HSR TCA configuration was defined and will be fabricated and tested to obtain data for validation of CFD viscous drag predictions on an HSR type configuration, Supersonic tests are planned in the Boeing Polysonic Wind Tunnel to obtain supersonic drag data at moderate Reynolds numbers The model was also planned to be tested in the NASA Langley NTF tunnel to obtain data for a wide range of Reynolds numbers.

• The final element is to recalculate the drag of the TCA to see if the variations between the theories has vanished and the theory predicts the test results.

•The elements that are crossed out have been canceled by reduction in program funding

Why the Interest in Flat Plate Turbulent Boundary layers ?

- First Step in Evaluating Navier Stokes Prediction Methods
- Help Sort Out Appropriate Turbulence Models
- Good Estimate of Viscous Drag of HSCT Type Configurations (Easy, Quick , Robust and Accurate)
- PD Drag Prediction Methods
- Extrapolation of Wind Tunnel Data to Flight Conditions
- δ Predictions Used to Size Diverter Height
- δ^* plus CF Predictions Used to Calculate Spillage and Internal Drag of Flow-Through Nacelles
- Quick Estimate of Surface Temperature
- Provides Physical Insight into Viscous Flow Characteristics

It is felt that the first step in validating the viscous drag predictions of any Navier Stokes code is to make sure that predictions of the local and average skin friction drag and boundary layer must match the “simple” flat plate measured test data over the range of Mach numbers and Reynolds for which the codes will be used. This process will help to evaluate the applicability of of the various turbulence models.

Because HSCT configurations have rather thin wings, slender bodies and low cruise lift coefficients, experience has shown that flat plate skin friction calculations provide good estimates of the viscous drag of HSCT type configurations. The predictions are easy, quick, robust and quite accurate.

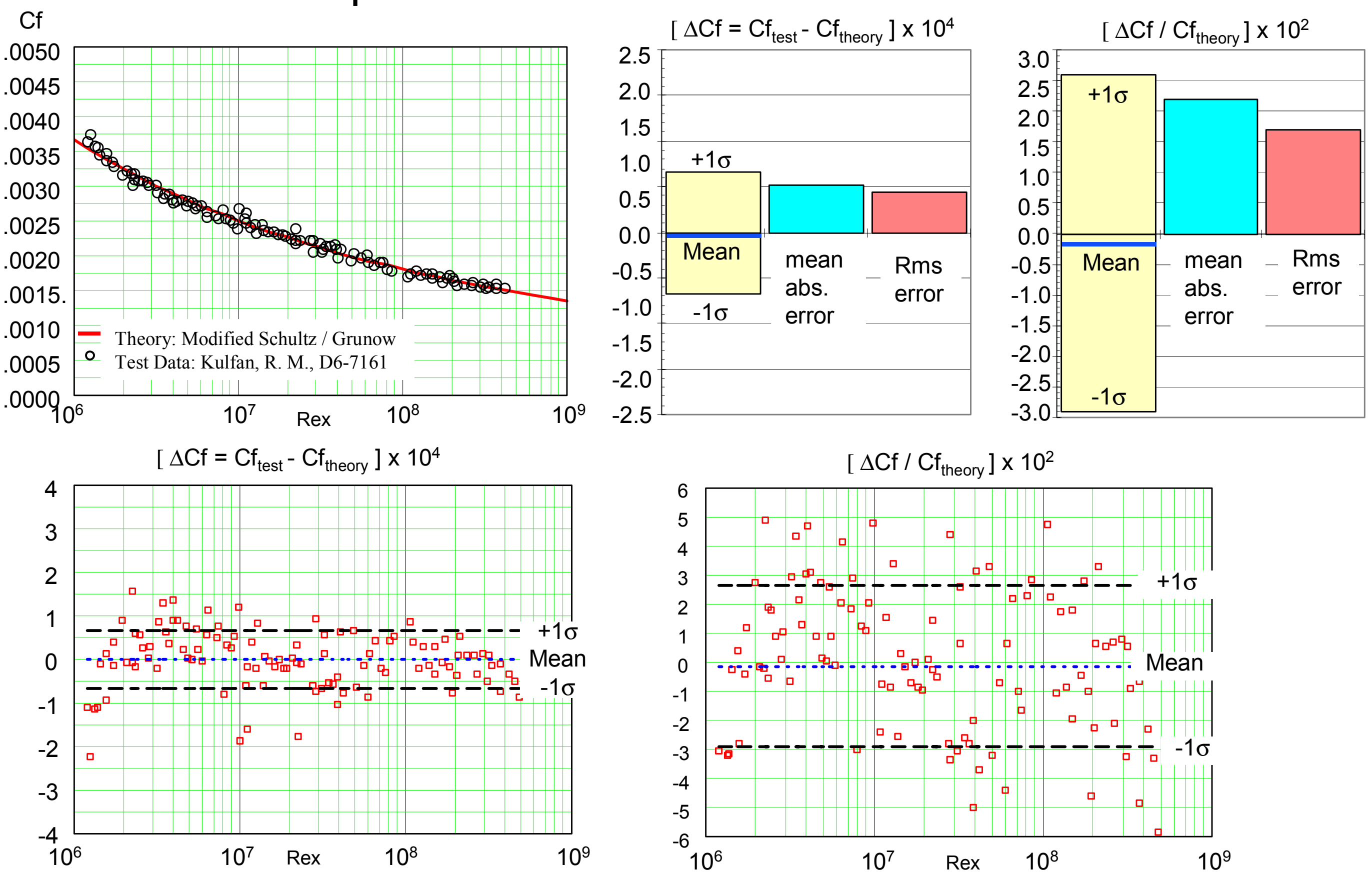
The current PD viscous drag prediction methods are based on flat plate skin friction drag calculations. Currently wind tunnel data is extrapolated to flight conditions using flat plate friction drag predictions.

Flat plate estimates of the boundary layer thickness are used as the preliminary criteria for specifying the boundary layer diverter height for the HSCT nacelle installations. Boundary layer displacement thickness predictions together with CF calculations are used to calculate the spillage and internal drag of wind tunnel flow though nacelles.

Local skin friction calculations corrected for local dynamic pressure effects can be used to estimate local surface temperatures.

The boundary layer thickness information presented in this note also provides some physical insight in to the fundamental features of turbulent flat plate flow.

Incompressible Local Skin Friction Data



Flat plate skin friction data was obtained from a number of experimental sources. These data cover a wide range of Mach numbers and Reynolds numbers. Comparisons were made with various flat plate theories to select the theory that most closely matches the test data. The results of these assessments are presented in the Reference shown below.

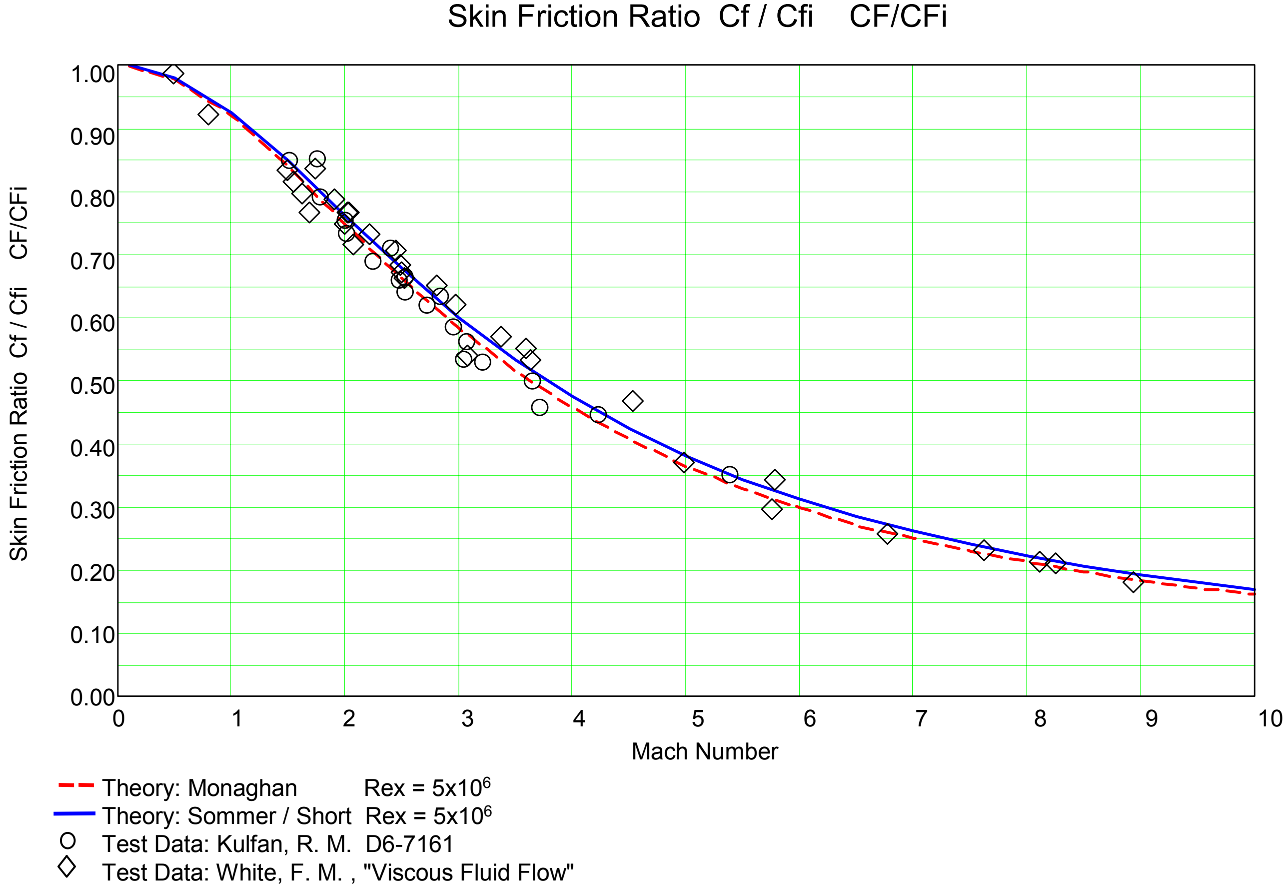
The flat plate theories are based on the reference temperature method. This method assumes that the incompressible skin friction equations apply to supersonic Mach numbers provided that the density and viscosity are calculate at some reference temperature that represents the variation of temperature across the boundary layer.

This figure shows the comparison of the modified Shultz / Grunow equation with incompressible test data. Statistical analysis of the differences between the test data and corresponding Cf predictions shows that the mean of the differences is ΔCf = -.000000671 which corresponds to an average difference of 0.13% .The standard deviation of data about the mean is approximately 0.7 counts of drag (ΔCf = 0.000067) which corresponds to 2.8% of the corresponding predicted value.

The modified Shultz / Grunow equation therefore appears to provide an accurate estimate of incompressible local skin friction coefficient over the entire range of Reynolds Numbers covered by the test data.

Reference: Kulfan, R. M., "Historic background on flat plate turbulent flow skin friction and boundary layer growth", HSR Airframe Technical Review, Feb 1998

Comparison of Compressibility Effects Predictions

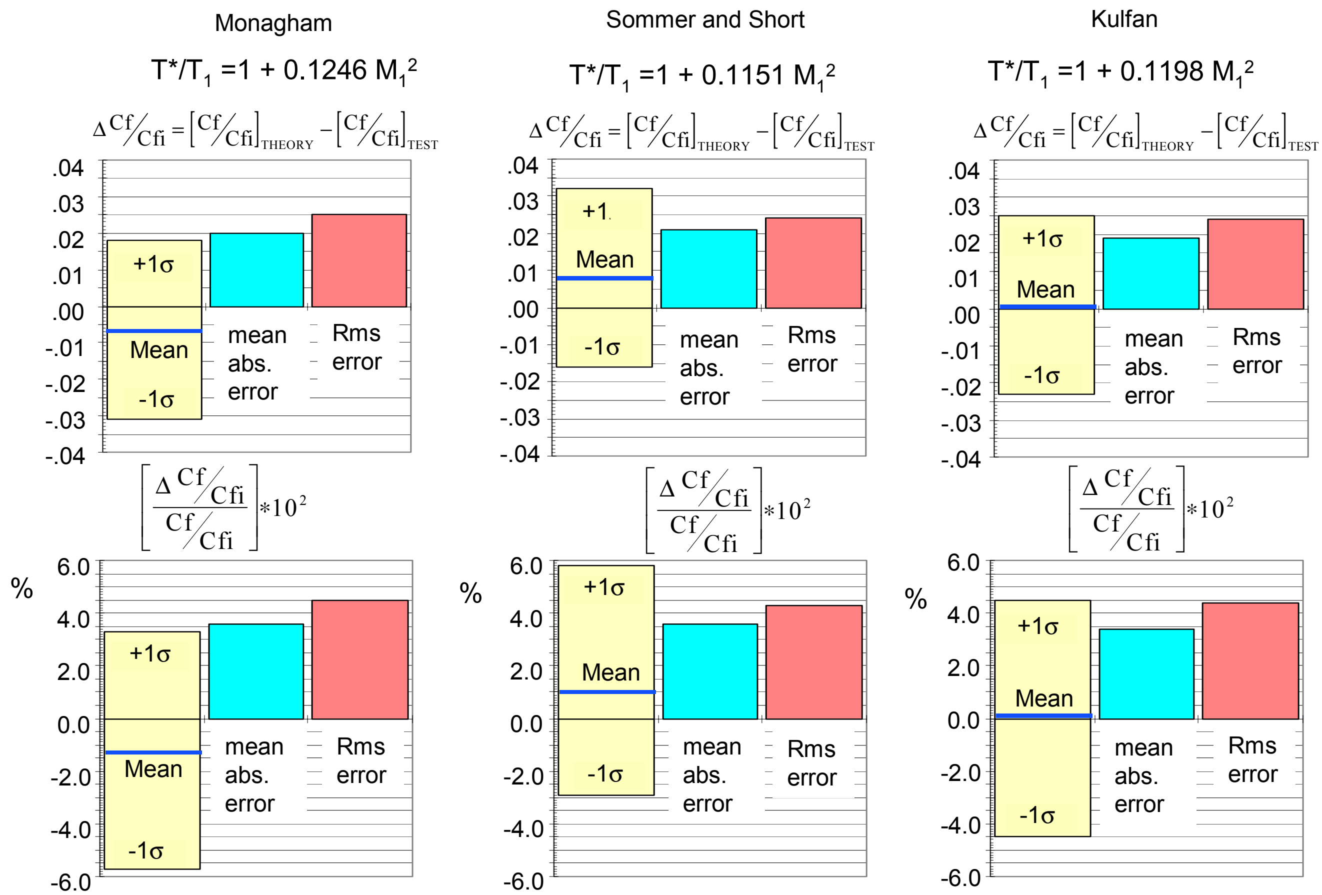


This figures shows some of the compressible flow skin friction data used to validate the flat plate theories. This compares the compressible skin friction predictions obtained using two commonly used T* methods, the Monaghan T* and the Sommer-Short T* method.

The Sommer-Short T* equation results in compressible skin friction values consistently higher than predicted using the Monaghan method. It was for this reason that the Boeing US SST program switched from the Monaghan method to the Sommer-Short method.

The full scale SST performance predictions were obtained from wind tunnel data corrected to full scale conditions. Wind tunnel skin friction drag is higher than the full scale conditions. Using higher skin friction values calculated by the Sommer -Short method resulted larger skin friction corrections. This resulted in higher L/D assessments for the SST.

Evaluation of Reference Temperature Equations



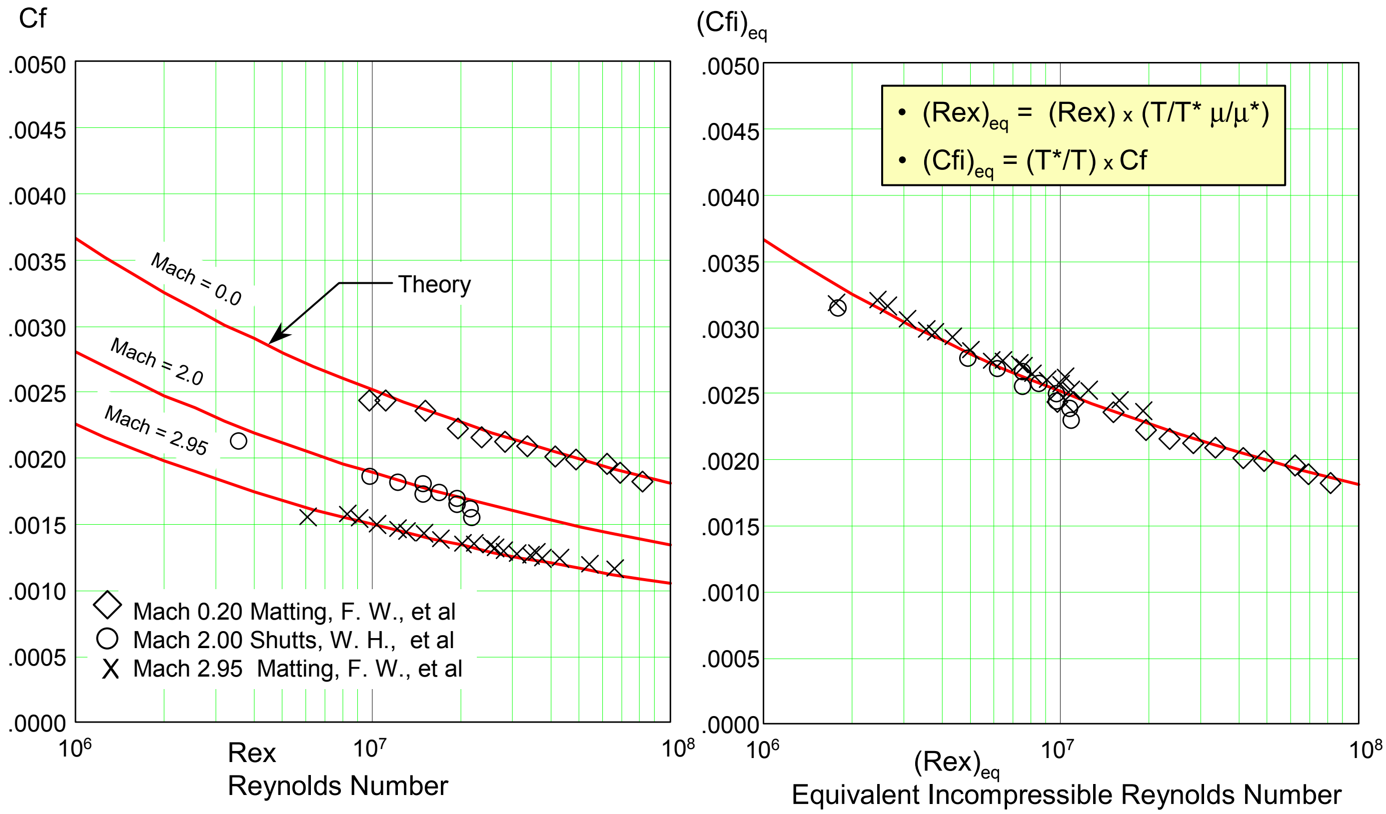
Statistical analyses were made of the differences between Cf predictions and the corresponding test data as shown in this figure . The theoretical predictions were obtained using three different T* equations.
The “scatter” in the test - theory increments are essentially equal. The mean of the differences between the test and theory, however differs between the predictions obtained using the different T* equations.

The “mean” of the theory - test differences obtained using the Monaghan T* equation is approximately 1% low. The “mean” of the theory - test differences obtained using the Sommer-Short T* equation is approximately 1% high. The constant for the Kulfan T* equation was therefore chosen to be the average of the Sommer-Short and the Monaghan constants.
This essentially resulted in a mean error between the test data and the theoretical predictions of zero.

The test data scatter about the mean has a standard deviation of about 4.5%. This large scatter is in part due to the variations of Reynolds number of the test data. The Reynolds number for the test data 10^6 to 10^7.

Conversion of Compressible Cf Data to Equivalent Incompressible $(Cfi)_{eq}$ Data

- Kulfan T* Method
- Modified Schultz-Grunow Cf Equation



The T* equations can also be used to convert the compressible skin friction to equivalent incompressible data. This transformation procedure, as shown in the Figure, "collapses" all of the test data about the incompressible skin friction curve. This approach can provide a convenient means to assess the accuracy of the theoretical methods to account for compressibility effects simultaneously over a range of Mach numbers and Reynolds numbers.

Conclusions - Flat Plate Database Developemnt

- Modified Incompressible Equations and Improved T*/T Method Predict "Mean" of Available Flat Plate Skin Friction Drag Measurements
- New Methods Presented That Appear to Provide Good Estimates of Boundary layer Thickness and Displacement Thickness
- Compressibility Effects Have Very Little Effect on The Shape or Height of the Turbulent Flat Plate Velocity Profile.
- Boundary Layer Displacement Thickness Increases Rapidly With Mach Number
- Comparisons of Navier Stokes CFD Predictions of Flat Plate Turbulent Skin Friction Drag and Boundary Layer Growth, With the Test Data and / or Theory Presented in This paper, is considered to be a Necessary and Vital Step to Validating the Codes For HSCT Viscous Drag Predictions .
- Need Additional / Quality Experimental CF Data:
    - Locate Available Existing Data
    - Symmetric Model Tests
    - Segmented Axisymmetry Body of Revolution
    - Utilize TU-144 Flight Test Data
    - ???

The modified incompressible CF equations and the improved T* equation presented in the reference paper appeared to consistently match the test better than the other flat plate CF methods currently in use on the HSCT program. It was recommended that the methods presented there, be adapted as the official HSCT flat plate calculation methods.
The boundary layer thickness, and displacement thickness calculations methods presented in that paper seem to be validated by the existing data.
Compressibility effects were shown to have little effect on either the shape or height of a turbulent boundary layer. The displacement thickness however varies rapidly with increasing Mach number.
A modified Shultz / Grunow incompressible local skin friction equation and the modified Prandtl / Schlichting average skin friction were used with the Kulfan T* equation in the studies reported in this paper to evaluate the CFD predictions of fully turbulent flow flat plate skin friction drag.

BPW-LB Skin Friction Analyses Analyses

- Code: CFL3D

- Average Skin Friction, CF

- Turbulence Models:
  * Baldwin - Lomax
  * Spalart - Allmaras
  * Menter's SST

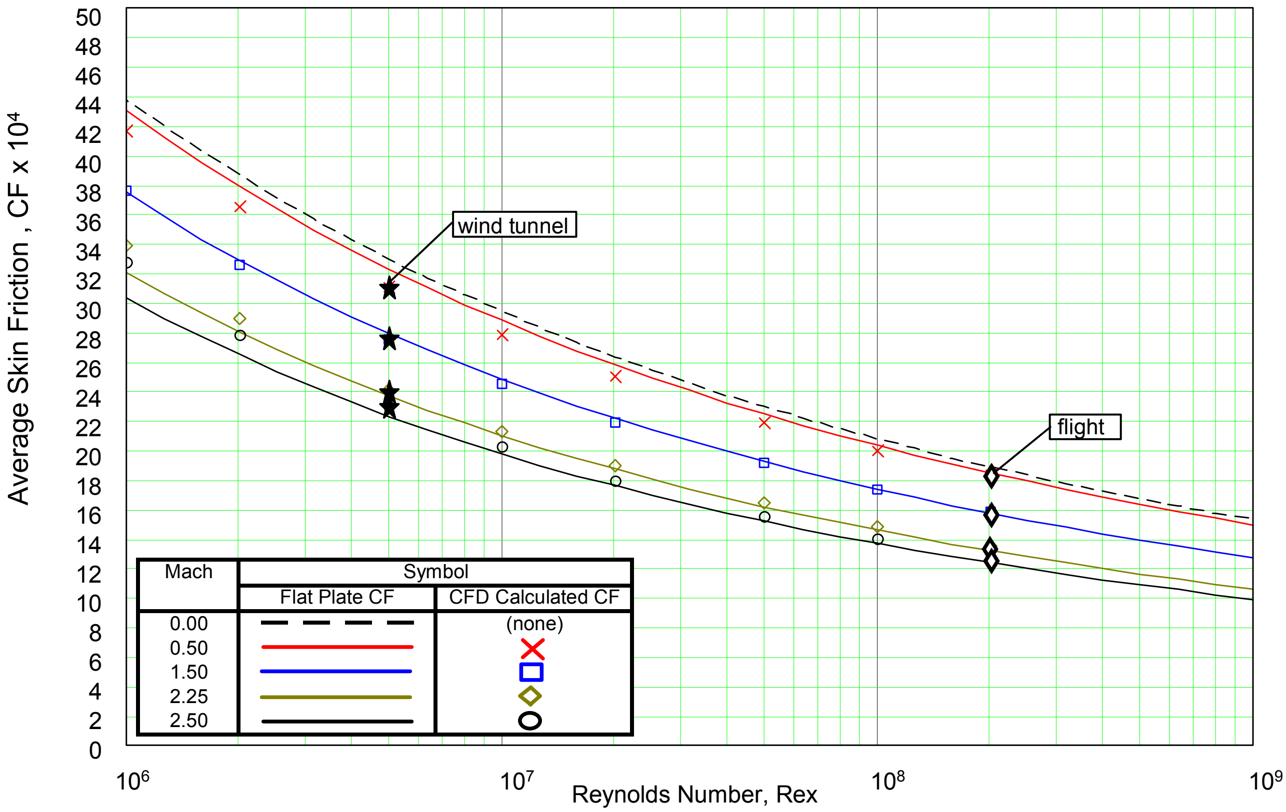
- Mach Numbers:
  * 0.5
  * 1.5
  * 2.25
  * 2.5

- Reynolds Number:
  * 10^6 to 200 x 10^8

The BPW-LB average skin friction predictions were made using CFL3D and a number of turbulence models for a range of Mach numbers and Reynolds as shown in the figure.

CFD Calculated Average CF Comparisons with Flat Plate CF

- BPW-LB CFL3D Code
- Baldwin - Lomax Turbulence Model

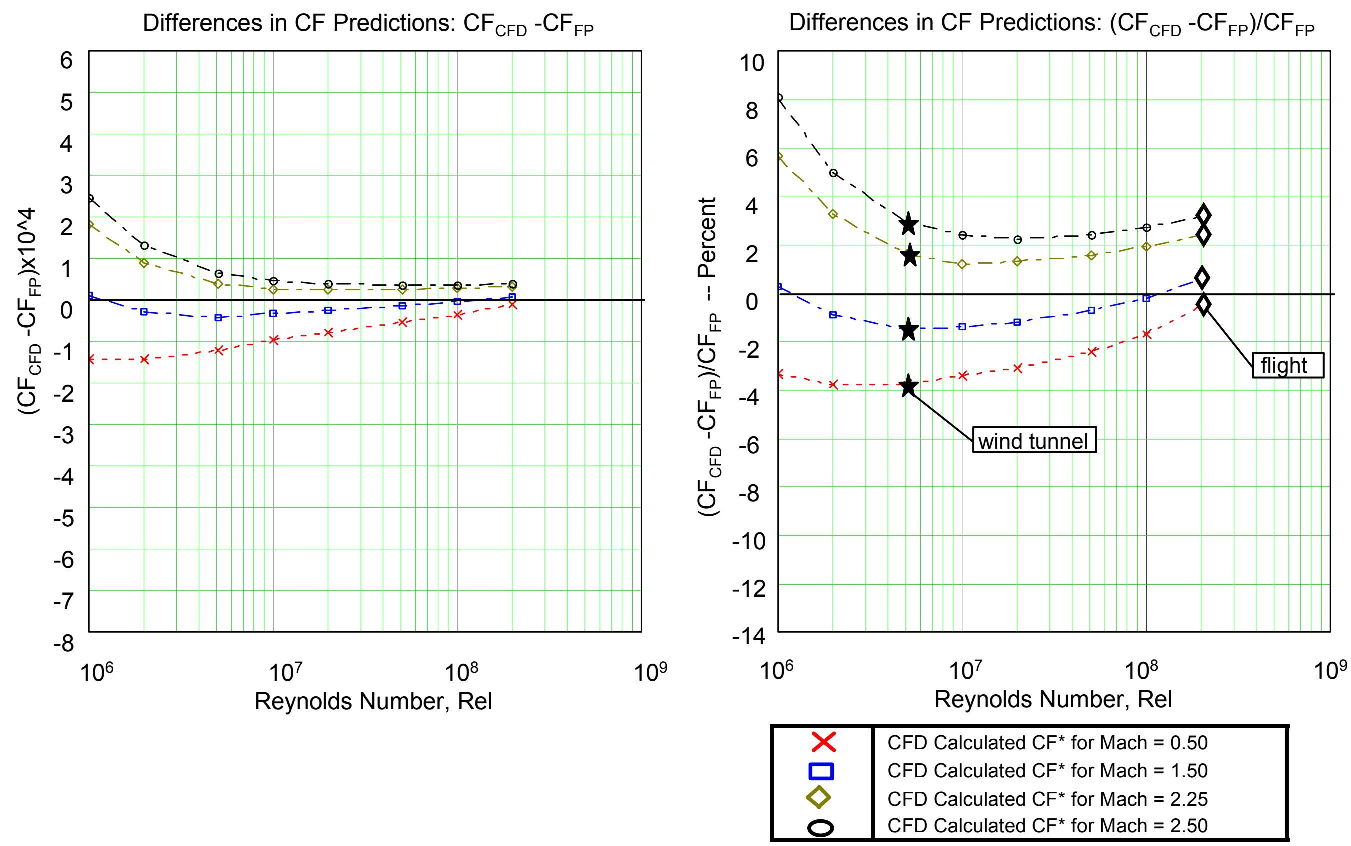


This compares average skin friction predictions obtained using the Baldwin - Lomax turbulence model, with the flat plate predictions. The Calculations were made for Mach = 0.5, 1.5, 2.25 and 2.5

The Reynolds numbers for typical wind tunnel conditions and for full scale or flight conditions are also shown.

Differences Between CFD Calculated CF and Flat Plate CF

- BPW-LB CFL3D Code
- Baldwin - Lomax Turbulence Model

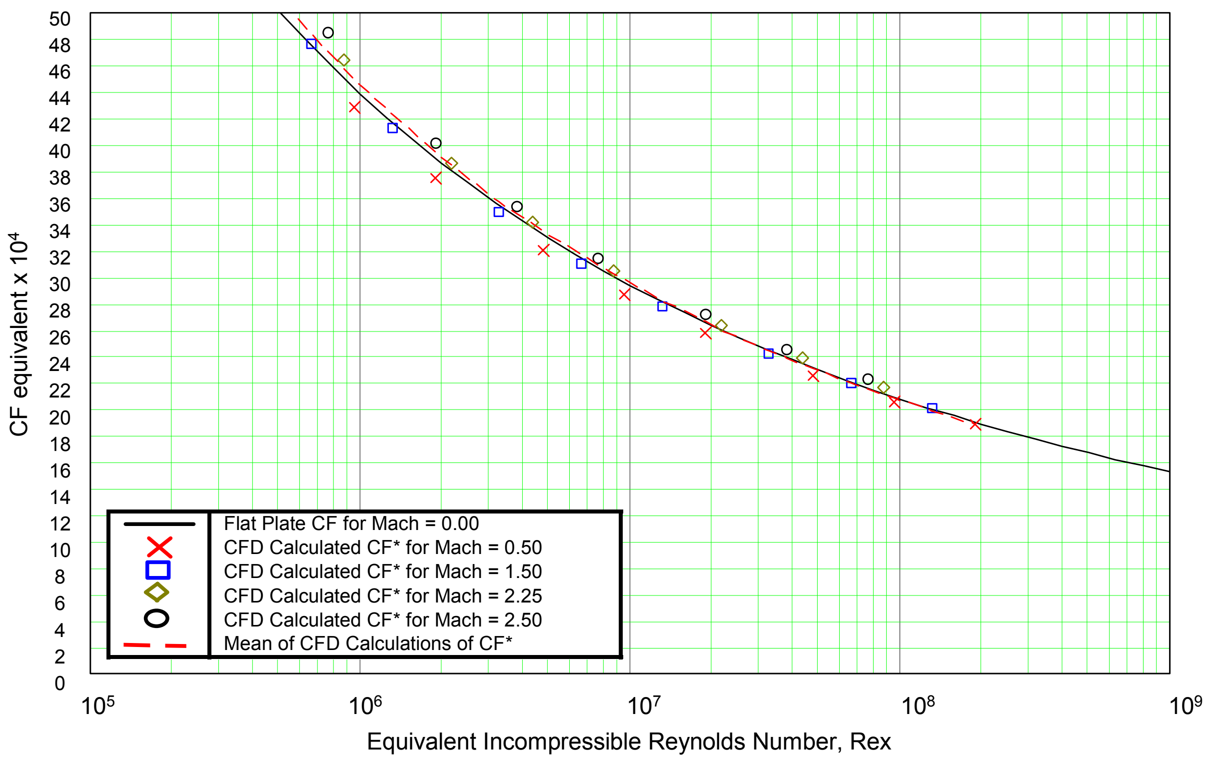


This shows the differences between the CFL3D predictions and the flat plate theory both as incremental differences, and as differences in percent.

The differences in the predictions are quite Mach number dependent. The errors in the predictions are relatively constant with Reynolds numbers between the wind tunnel and the flight conditions.

Equivalent Incompressible Average Skin Friction Calculations

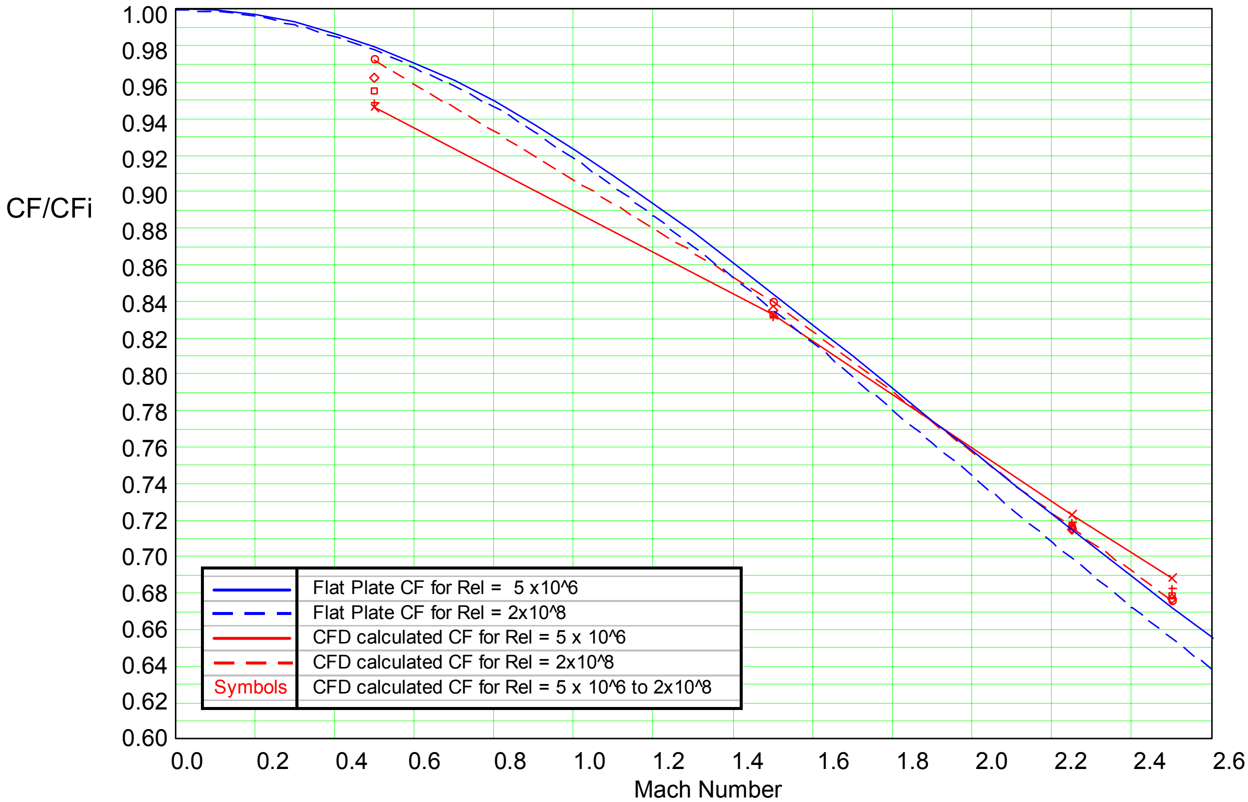
- BPW-LB CFL3D Code
- Baldwin - Lomax Turbulence Model



The Kulfan T* equation was used to transform the CFL3D predictions to incompressible skin friction data. The dash red line in this picture is the mean of the CFL3D predictions. It appears that the CFL3D predictions with the Baldwin-Lomax turbulence matched the flat plate predictions and the variation of CF with Reynolds number reasonably well.

Average Skin Friction Calculations: CF /CFi

- BPW-LB CFL3D Code
- Baldwin - Lomax Turbulence Model
- Wind to Flight Reynolds Numbers

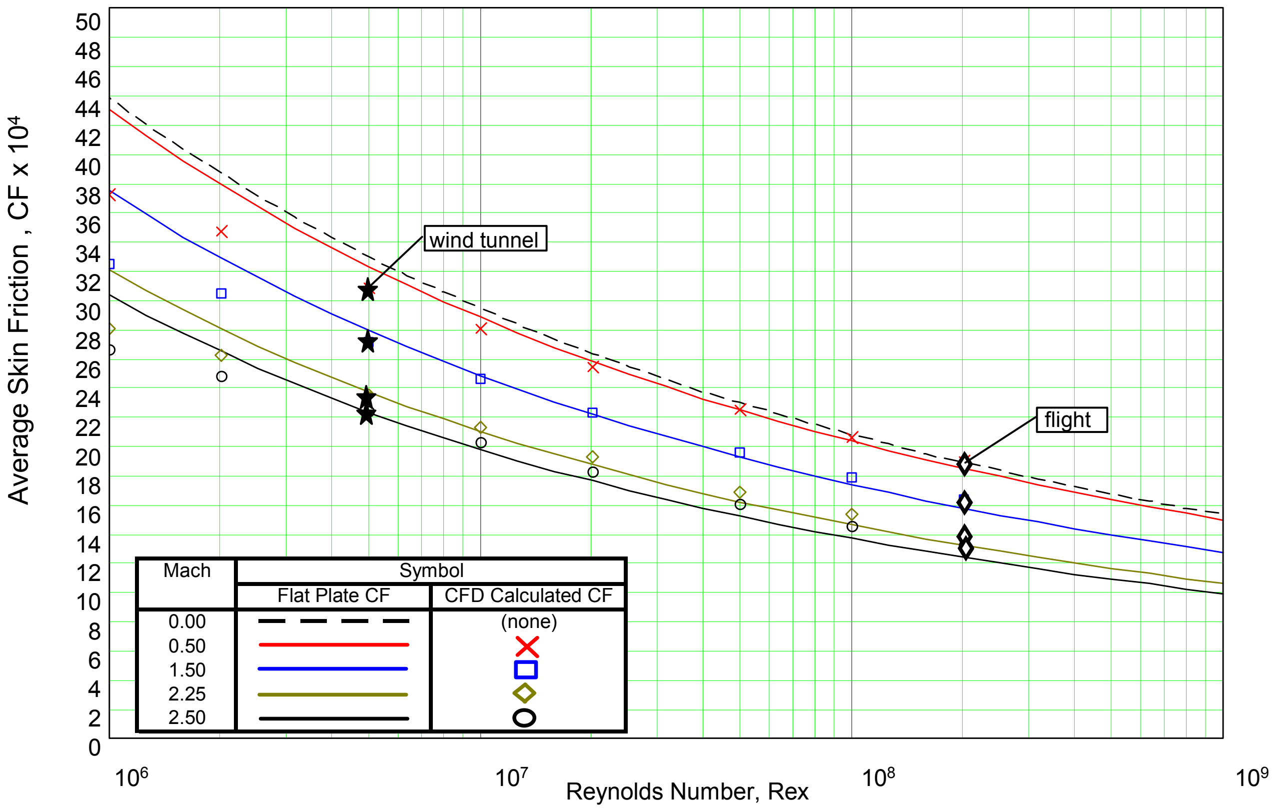


The ratio of CFD calculated skin friction coefficients divided by the flat plate incompressible skin friction coefficient at the same Reynolds number, CF/CFi , is shown plotted versus Mach number. This process tends to normalize the effect of Reynolds number and readily indicates the effect of Mach number on the skin friction drag. The compressibility effect predicted by the CFD is less then that from the flat plate theory.

Again is is evident that CFD values of CF are to low at low Mach numbers and too high at the higher Mach numbers.

CFD Calculated Average CF Comparisons with Flat Plate CF

- BPW-LB CFL3D Code
- Spalart - Allmaras Turbulence Model

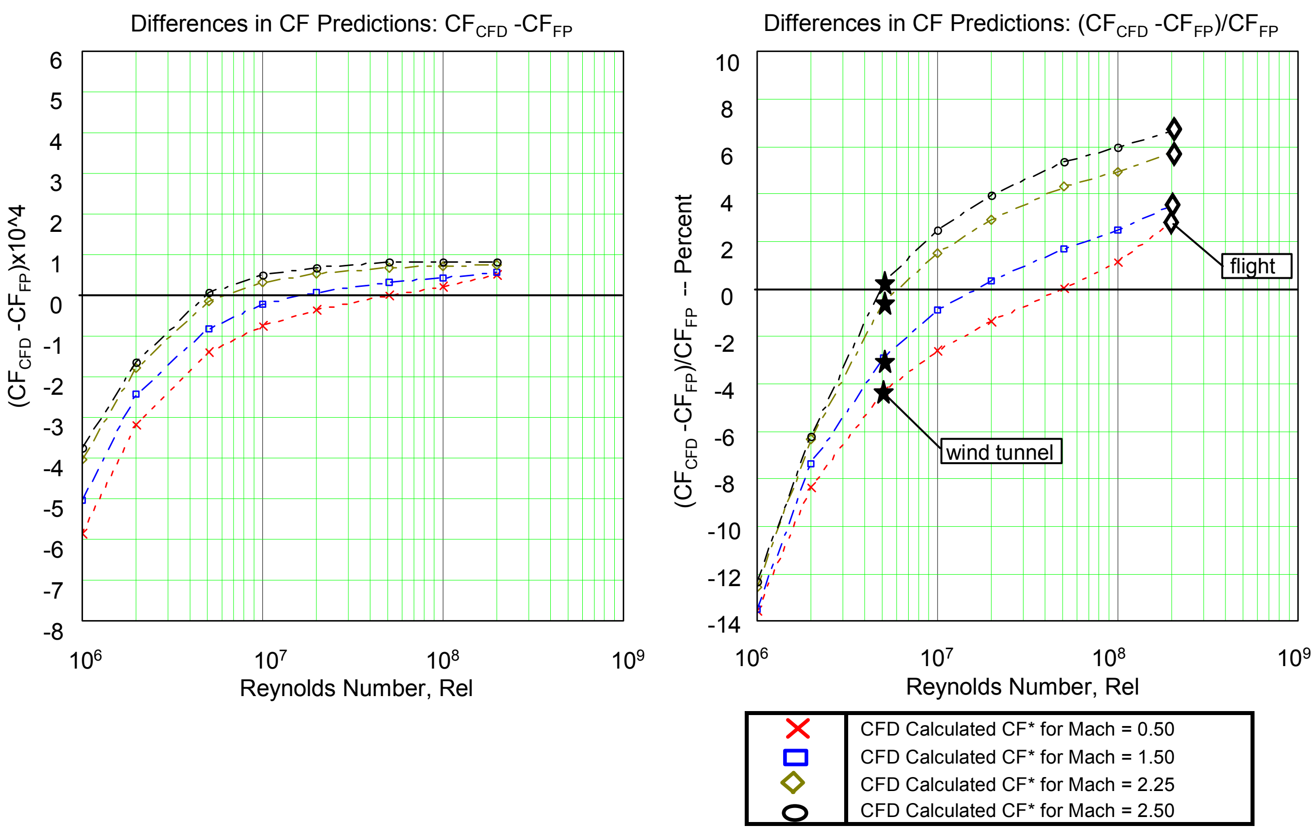


This shows the values of CF, calculated using the Spalart - Allmaras turbulence mode, compared with the corresponding flat plate theory values. The CFD predictions of CF are seem to be significantly less then the flat plate theory at the lowest Reynolds numbers.

Later in this paper it will be shown that the Spalart - Allmaras CF predictions have a laminar flow type characteristics at the lowest Reynolds numbers. This is then followed by a transitional type flow and finally turbulent flow at the higher Reynolds numbers.

Differences Between CFD Calculated CF and Flat Plate CF

- BPW-LB CFL3D Code
- Spalart - Allmaras Turbulence Model

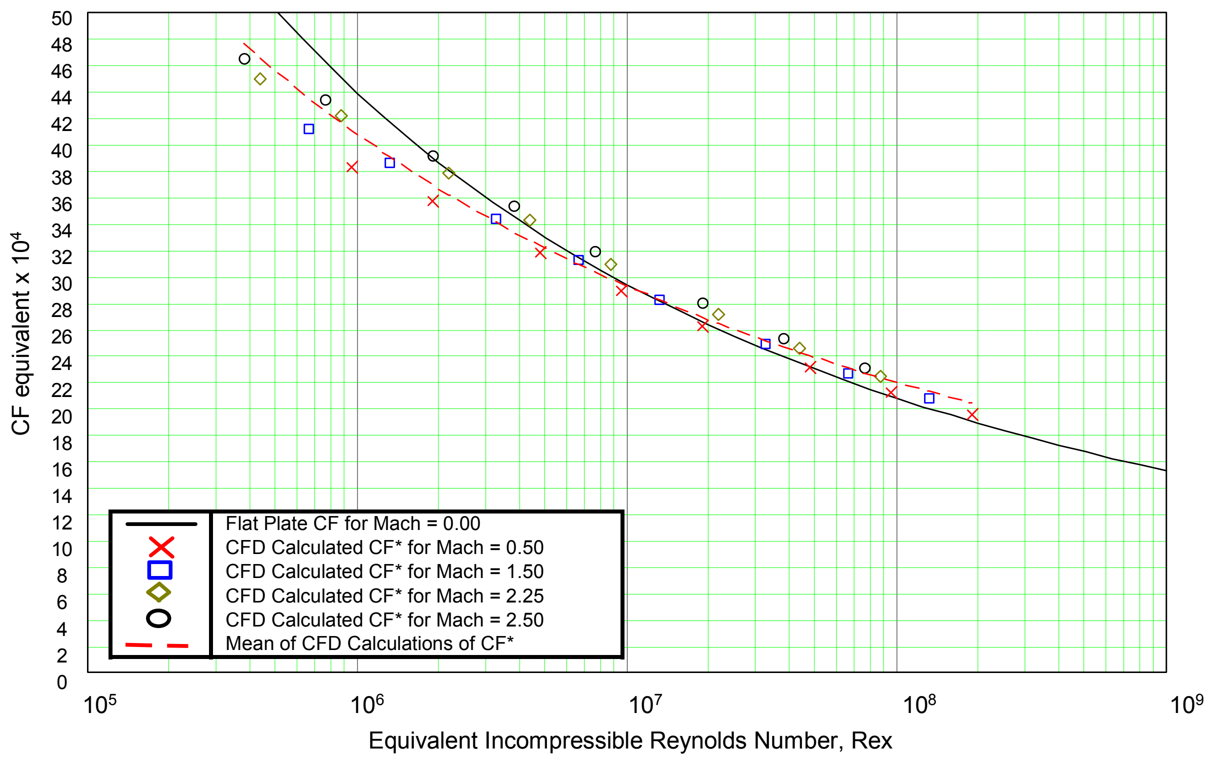


This shows the differences between the CFD and the flat plate CF predictions both as incremental drag counts and in percent.

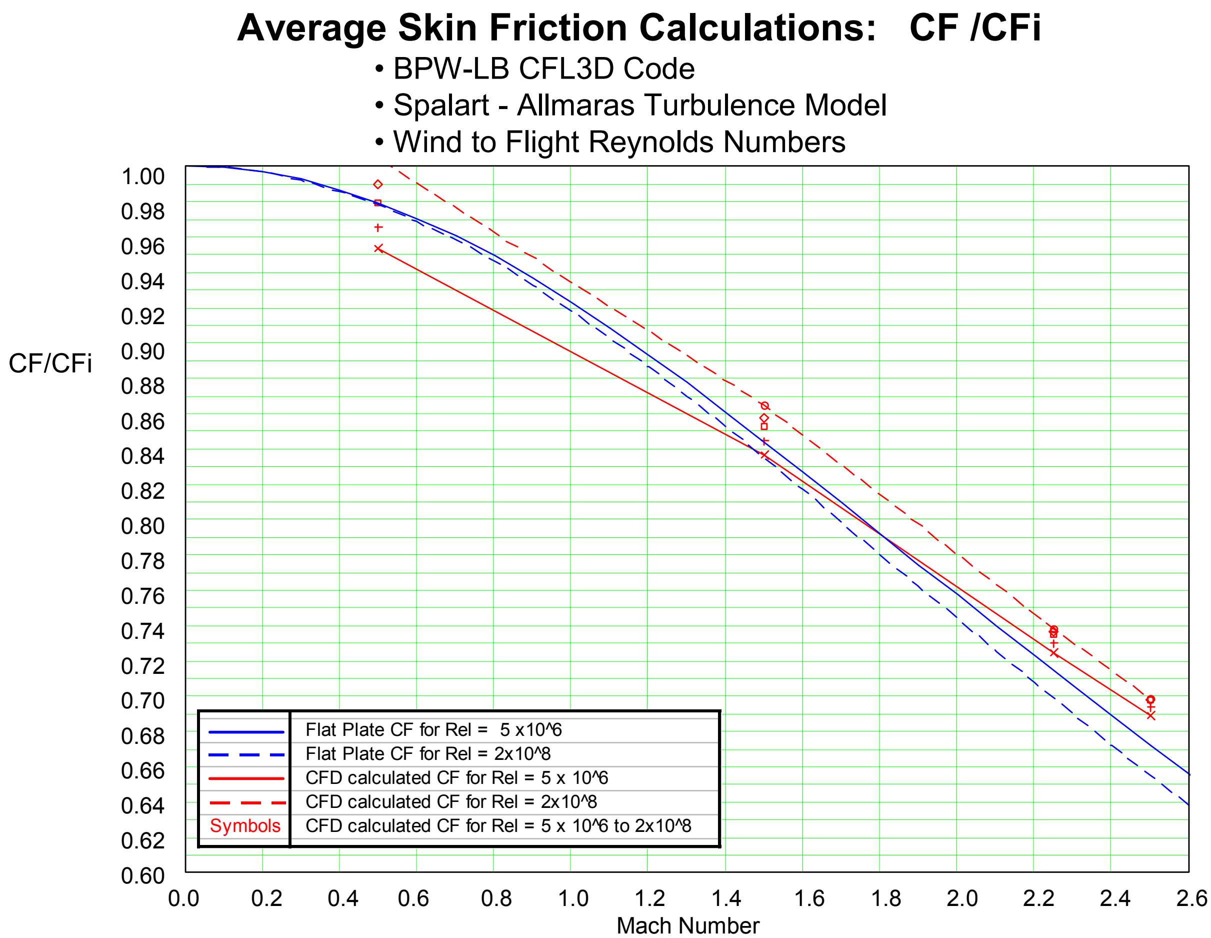
The predicted variation of CF with Reynolds obtained using the Spalart - Allmaras turbulence model is significantly different then the flat plate theory especially at the lower Reynolds numbers. The errors in the skin Friction predictions with this turbulence model are dependent both on Mach number and Reynolds number.

Equivalent Incompressible Average Skin Friction Calculations

- BPW-LB CFL3D Code
- Spalart - Allmaras Turbulence Model



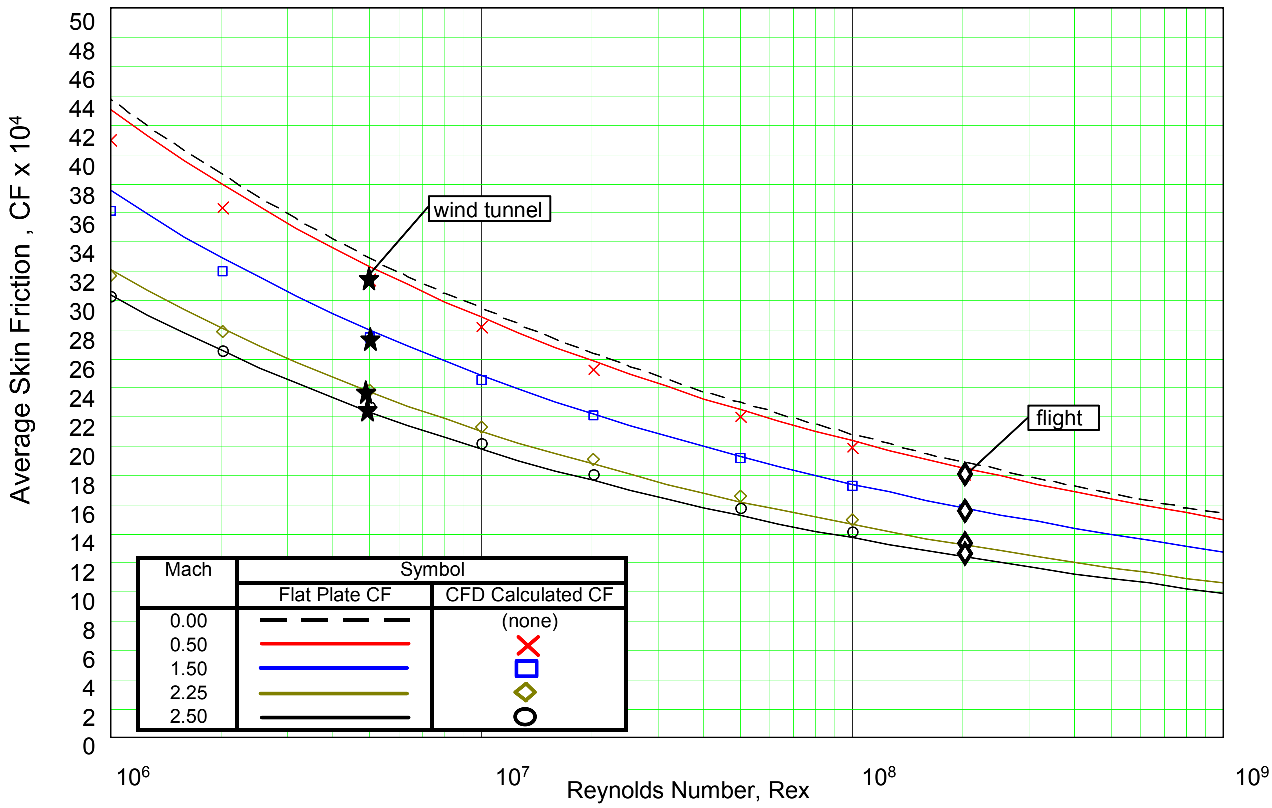
The Kulfan T* method was used to adjust the CFD calculations of CF to equivalent incompressible skin friction coefficients. The results shown in the figure clearly show the differences in the variation of skin friction drag with Reynolds numbers calculated using the Spalart - Allmaras turbulence model compared to the flat plate theory.



The ratio of calculated CF to the flat plate incompressible CF indicate that Spalart - Allmaras calculation have the same Mach number trends as the flat plate theory. The friction drag predictions at the higher mach numbers are higher then the flat plate theory.

CFD Calculated Average CF Comparisons with Flat Plate CF

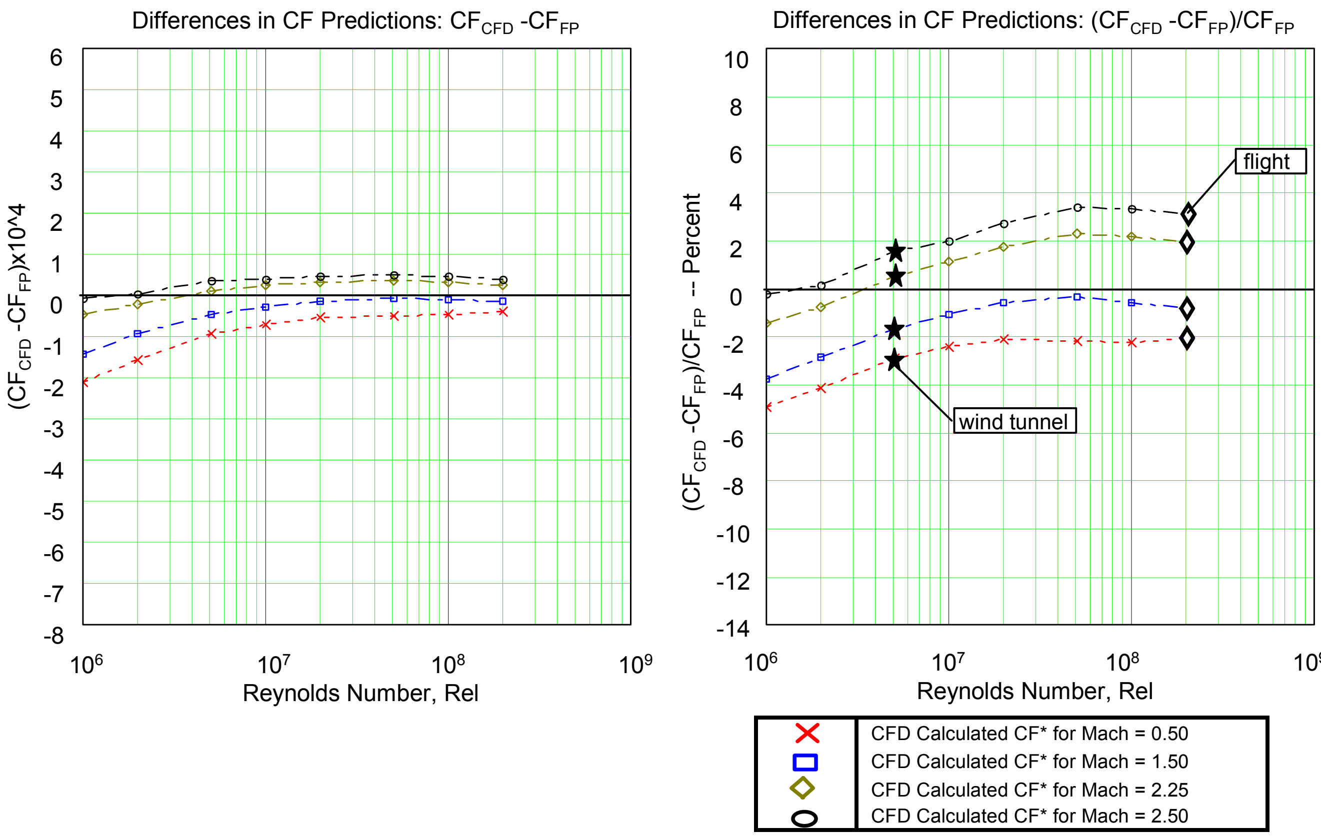
- BPW-LB CFL3D Code
- Menters Turbulence Model



CF calculations made by BPW-LB were also obtained using the Menter's SST turbulence model. The results are compared with the flat plate predictions in this figure.

Differences Between CFD Calculated CF and Flat Plate CF

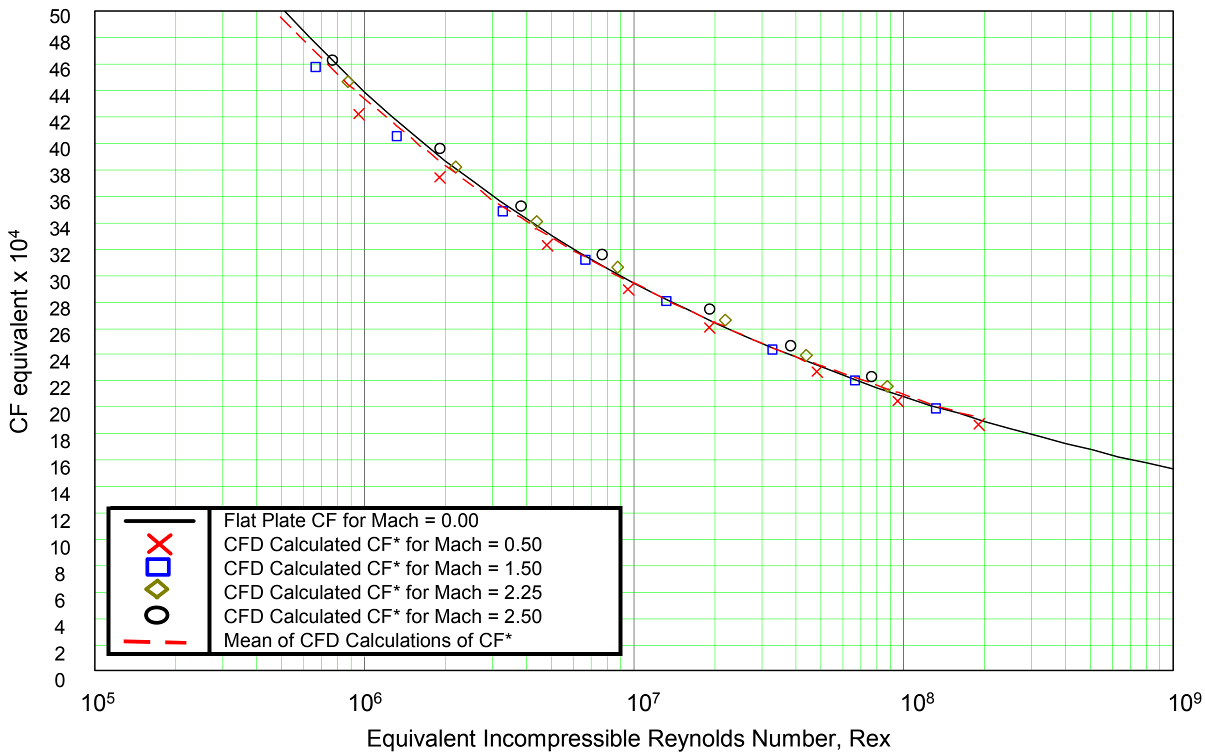
- BPW-LB CFL3D Code
- Menters Turbulence Model



The differences between the CFD and the flat plate calculations are approximately -1 count (-0.0001) to + 0.5 counts for all of the calculations above typical wind tunnel test Reynolds number (~ 6.4 $x10^6$). One count of skin friction drag corresponds to nearly 3.5 counts of airplane drag since the wetted area ratio for a typical HSCT is on the order of 3.5. Again there is a difference between the CFD and the flat plate CF predicted variations with both Reynolds Number and with Mach number.

Equivalent Incompressible Average Skin Friction Calculations

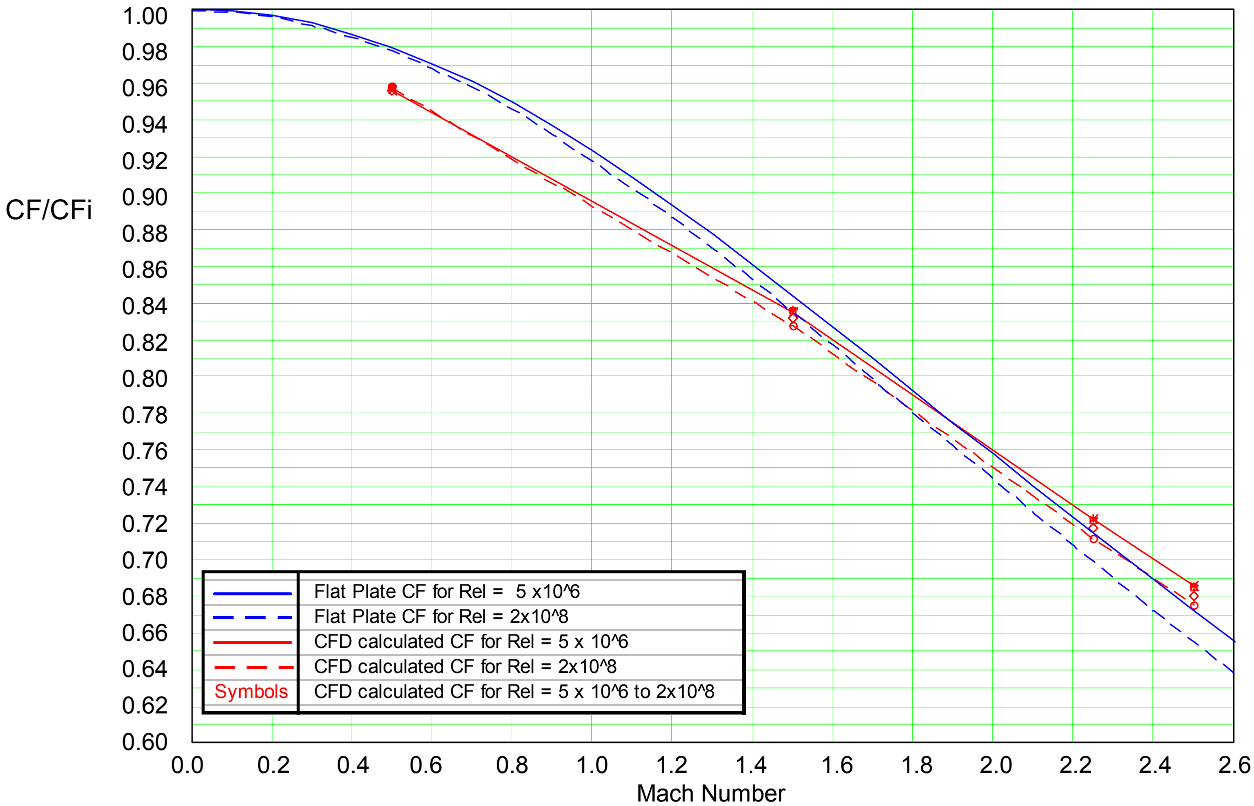
- BPW-LB CFL3D Code
- Menters Turbulence Model



The equivalent Cfi calculations show that the Reynolds number trends obtained with the Menter's SST model are quite similar to the flat plate theory trends.

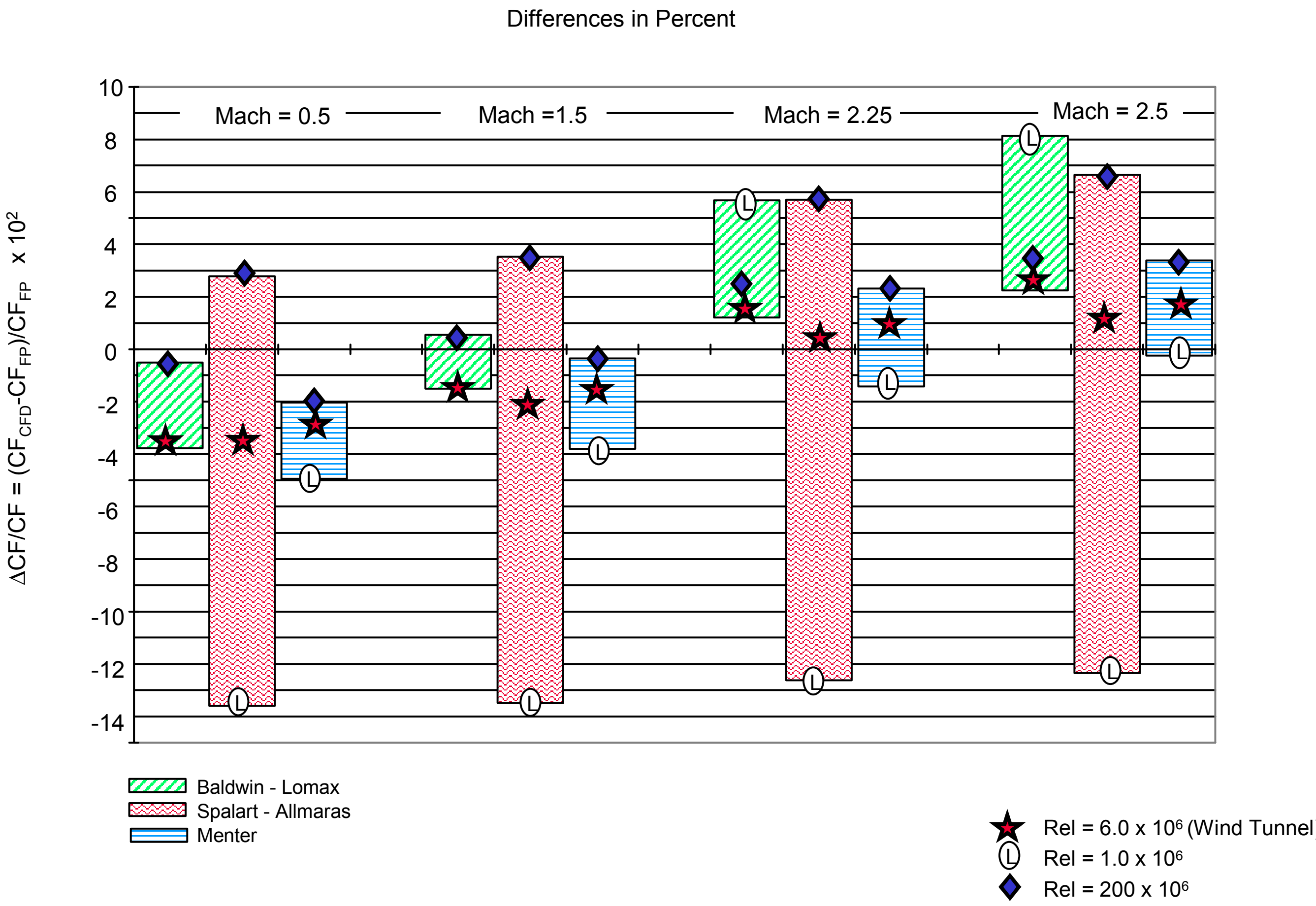
Average Skin Friction Calculations: CF /CFi

- BPW-LB CFL3D Code
- Menters Turbulence Model
- Wind to Flight Reynolds Numbers



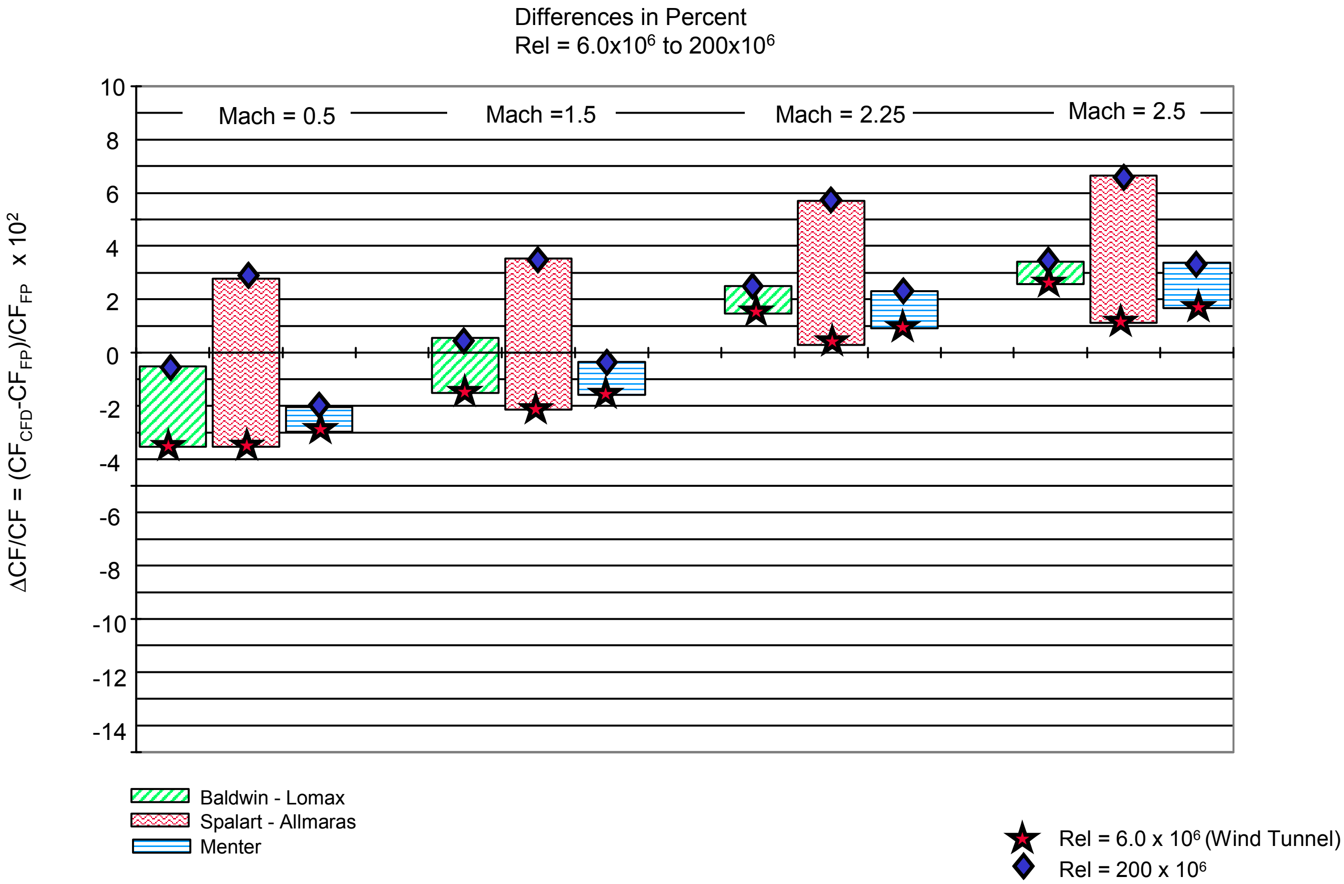
Again the CFL3D calculations of the compressible to incompressible skin friction coefficients show that the CFL3D calculations are lower then the flat plate predictions at the low Mach Numbers and tend to be slightly higher at the higher Mach numbers.

BLB CFL3D Flat Plate Viscous Drag vs Flat Plate Skin Friction Drag Calculations



This summarizes the comparisons of the CFL3D predictions with the flat plate theory for the complete range of analysis conditions. The greatest differences tend to be for low Reynold Numbers below wind tunnel conditions which really of little interest for most HSCT applications.

BLB CFL3D Flat Plate Viscous Drag vs Flat Plate Skin Friction Drag Calculations



This summarizes the comparisons of the CFL3D with the flat plate theory shown on the previous figure , but with the low Reynolds number results removed.

It is seen that the predictions obtained with all of the turbulence models at wind tunnel Reynolds numbers are quite consistent.

At Flight Reynolds numbers the Baldwin - Lomax and the Menter's SST results are nearly the same. The Spalart -Allmaras predictions are as few percent higher.

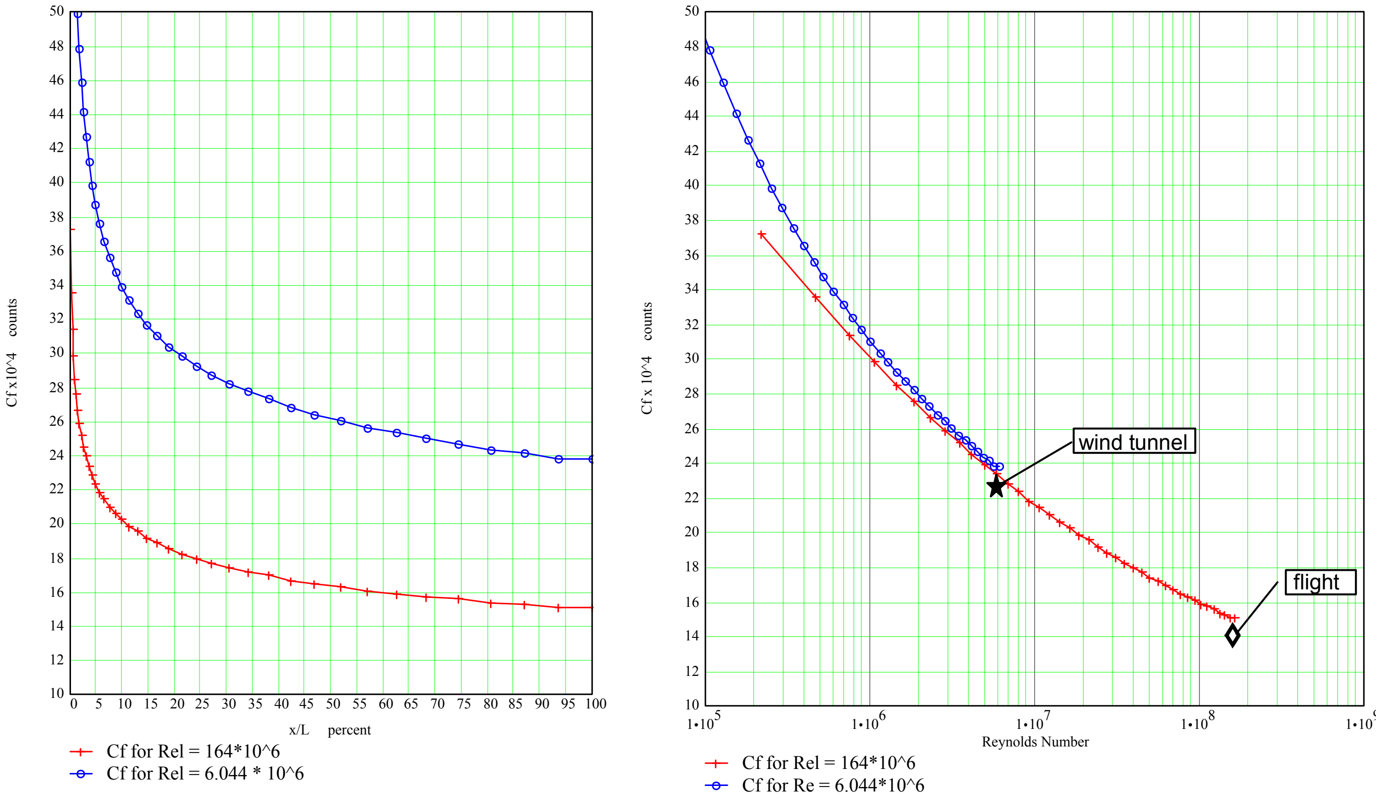
BCA Flat Plate Skin Friction Analyses

- Code: OVERFLOW
- Local Skin Friction, Cf
- Average Skin Friction, CF
- Turbulence Models:
  * Baldwin - Lomax
  * Spalart - Allmaras
  * Menter's SST
  * Baldwin - Barth
  * k - e
  * k - w
- Grid vertical spacing variations
- Mach Numbers:
  * 0.9
  * 2.4
- Reynolds Number:
  * 10^5 to 6 x 10^6
  * 10^5 to 200 x 10^8

The flat plate skin friction calculations by Boeing Commercial Aircraft in Seattle (BCA) , were obtained with the OVERFLOW code using a number of different turbulence models and different vertical grid spacing. Both local and average skin friction was calculated at Mach 0.9 and 2.4 for a typical wind tunnel Reynolds number and a typical flight Reynolds number.   Local skin friction was calculated for different locations on the flat plate. Integration of the local skin friction results then gave predictions of average skin friction for a wide range of Reynolds numbers based on the distance back of the leading edge of the flat plate.

BCA OVERFLOW Local Skin Friction Calculations, Cf

Mach = 0.9: Baldwin - Lomax Turbulence Model
Unform vertical grid spacing



This shows the calculated local skin friction coefficients plotted both in terms of local Reynolds number and the fractional distance along the flat plate for a Mach number of 0.9. Two different unit Reynolds were used for the calculations. The lower unit Reynolds number produced overall length Reynolds numbers corresponding to wind tunnel conditions. The higher unit Reynolds numbers produced overall length Reynolds numbers corresponding to full scale conditions. The two series of calculations depart from one another at the lowest distance Reynolds numbers. It is felt that the results obtained with the lower unit Reynolds number are more accurate for the lower distance Reynolds numbers because the grid density would be much higher then for the high unit Reynolds numbers. The OVERFLOW calculations shown here and in subsequent comparisons were obtained with a constant vertical grid spacing. The impact of using a stretched vertical grid near the surface will be discussed later in the paper.

BCA OVERFLOW Local Skin Friction Calculations, Cf

Mach = 2.4: Bladwin - Lomax Turbulence Model

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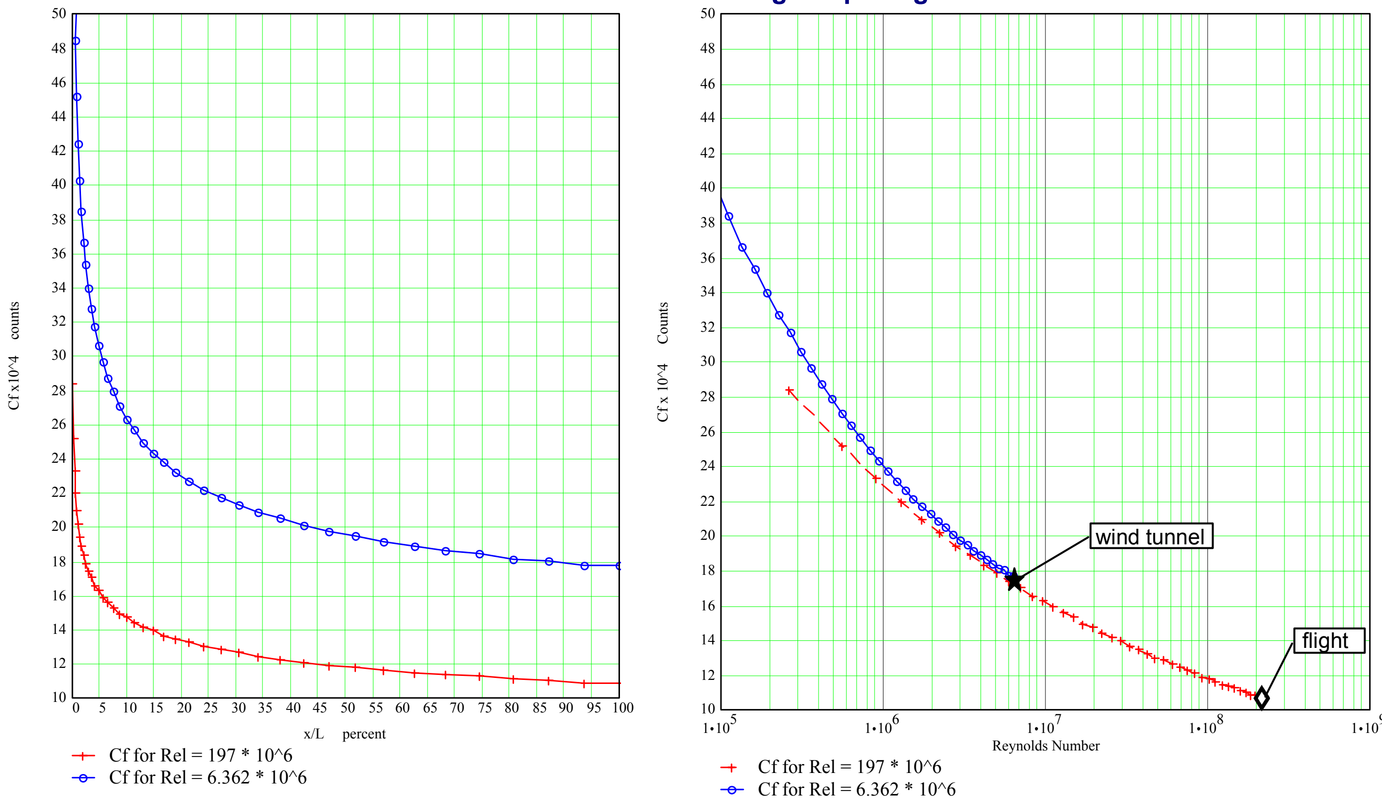
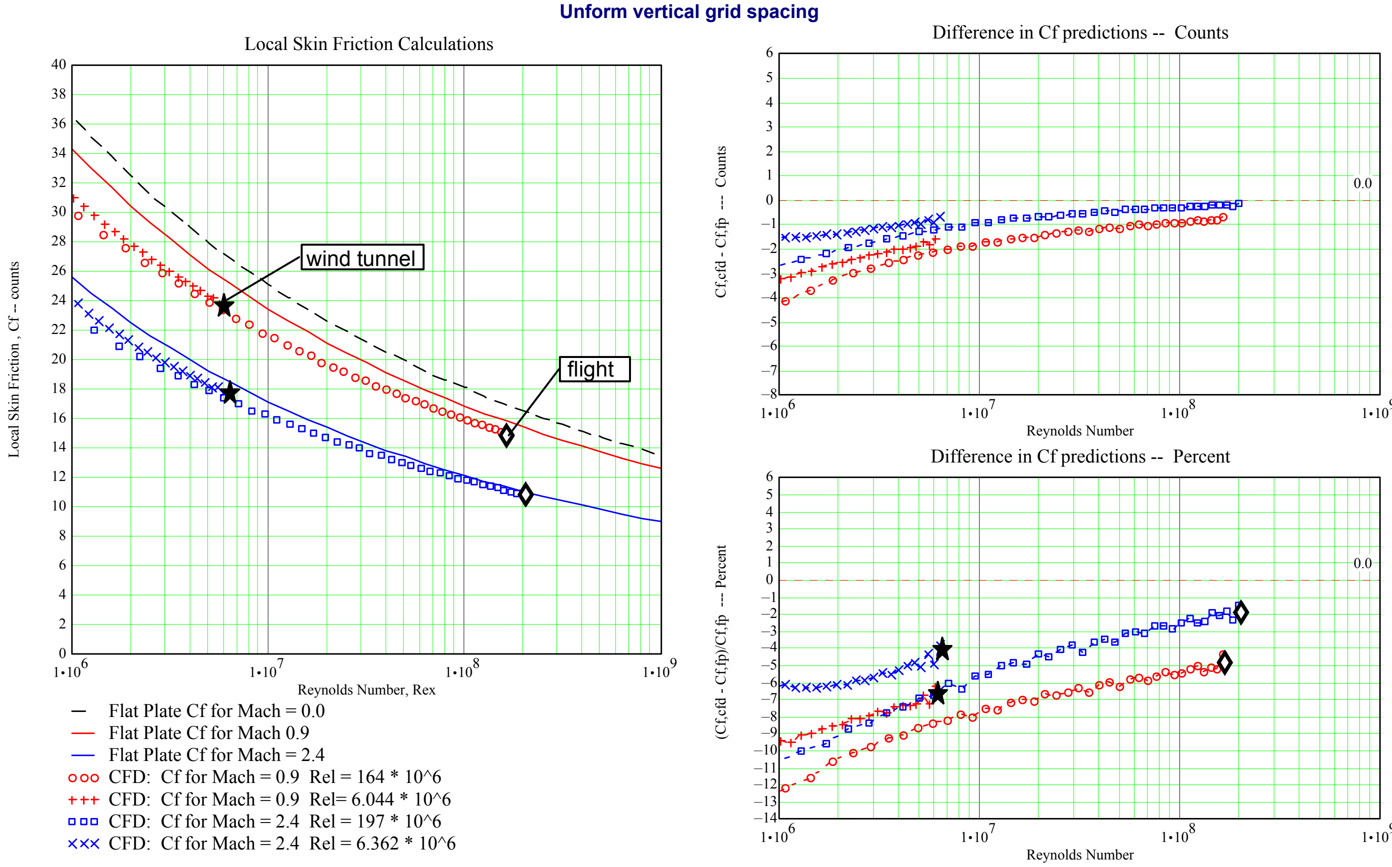


These are the similar results for the supersonic Mach number of 2.4. Again it is seen that calculations depart for the lower distance Reynolds numbers. The most accurate calculations are those corresponding to the end of the plate calculations as indicated by “wind tunnel “ and “flight” in the figure.

BCA OVERFLOW Local Skin friction Calculations Comparisons with Flat Plate Cf

Baldwin - Lomax Turbulence Model

Unform vertical grid spacing

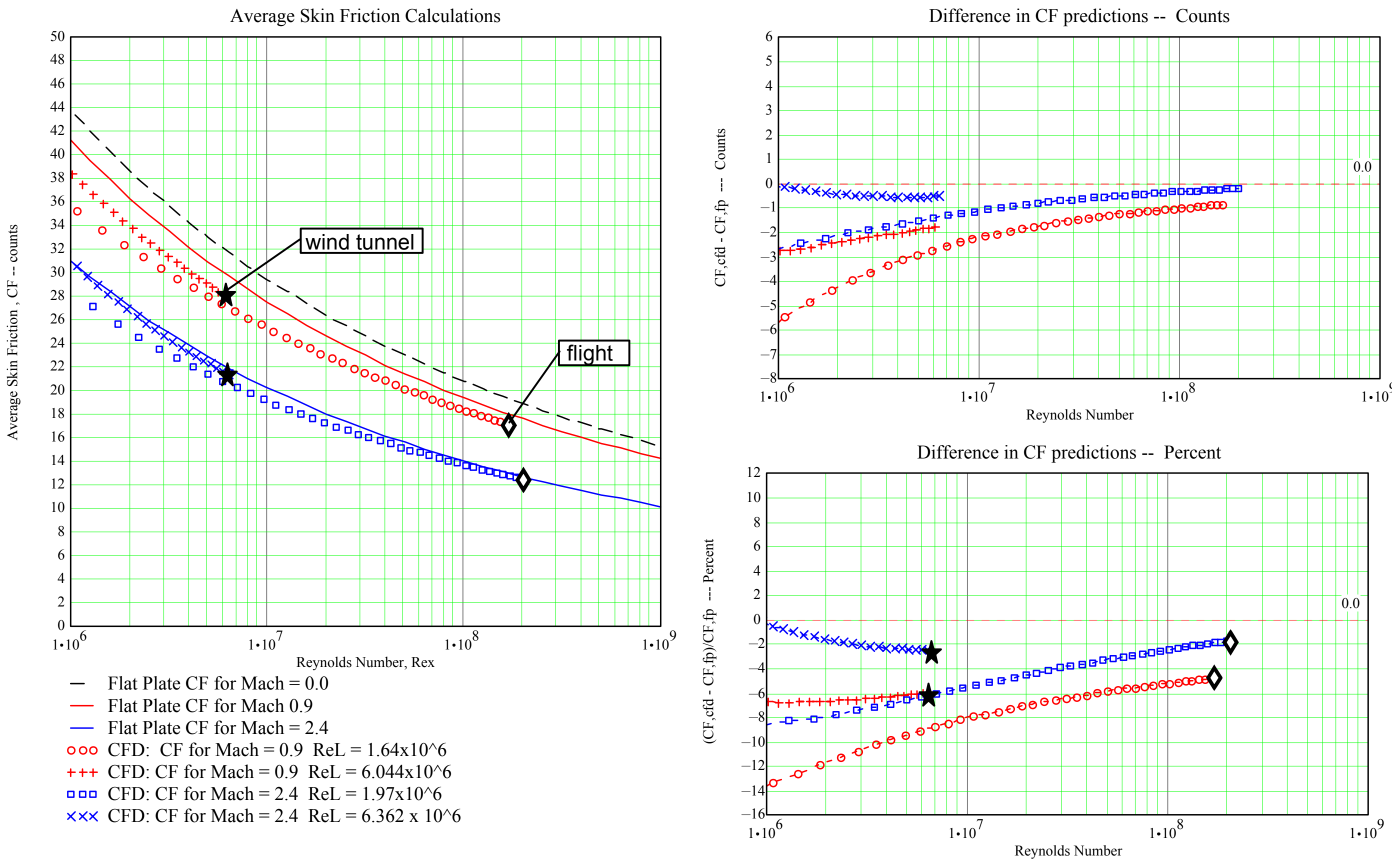


This compares the OVERFLOW local Cf predictions with flat plate theory. The overflow predictions are significantly less then the flat plate theory.

BAC OVERFLOW Average Skin friction Calculations Comparisons with Flat Plate CF

Baldwin - Lomax Turbulence Model

Unform vertical grid spacing



This is the corresponding average skin friction comparisons between the OVERFLOW predictions and the flat plate theory.
The OVERFLOW predictions are approximately 5% to 6 % lower then the flat plate theory at Mach 0.9, and 2% to 3% low at Mach 2.4.

BCA OVERFLOW Local Skin Friction Calculations, Cf

Mach = 0.9: Spalart - Allmaras Turbulence Model

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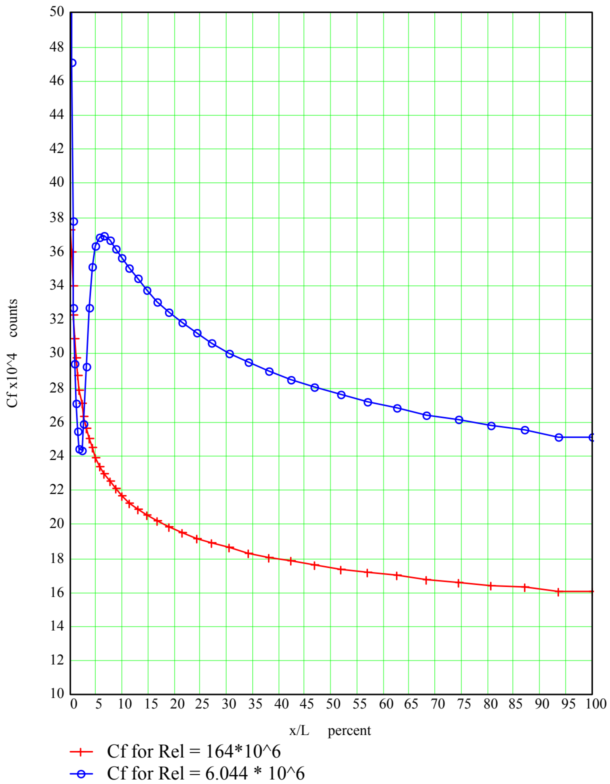
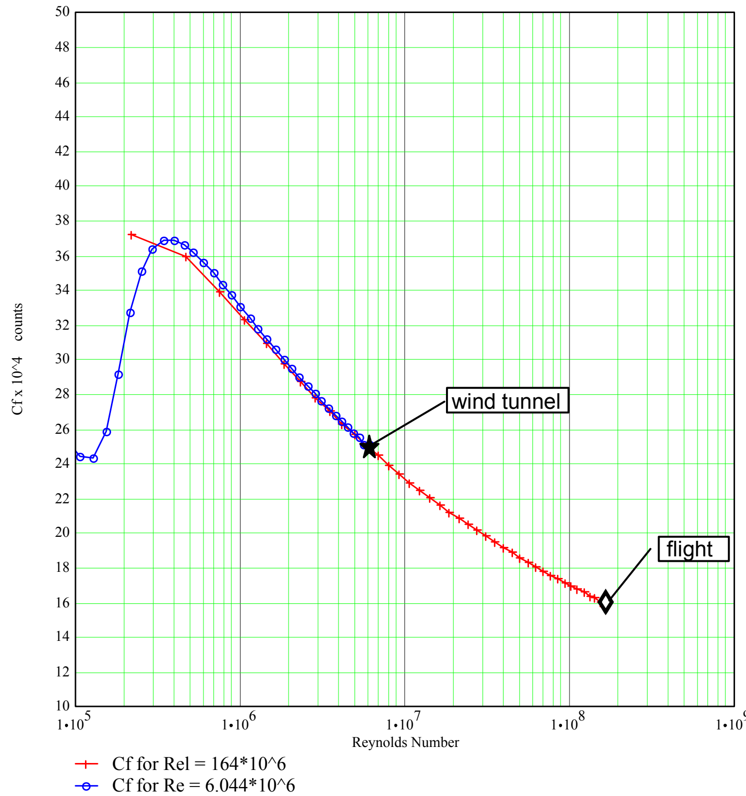


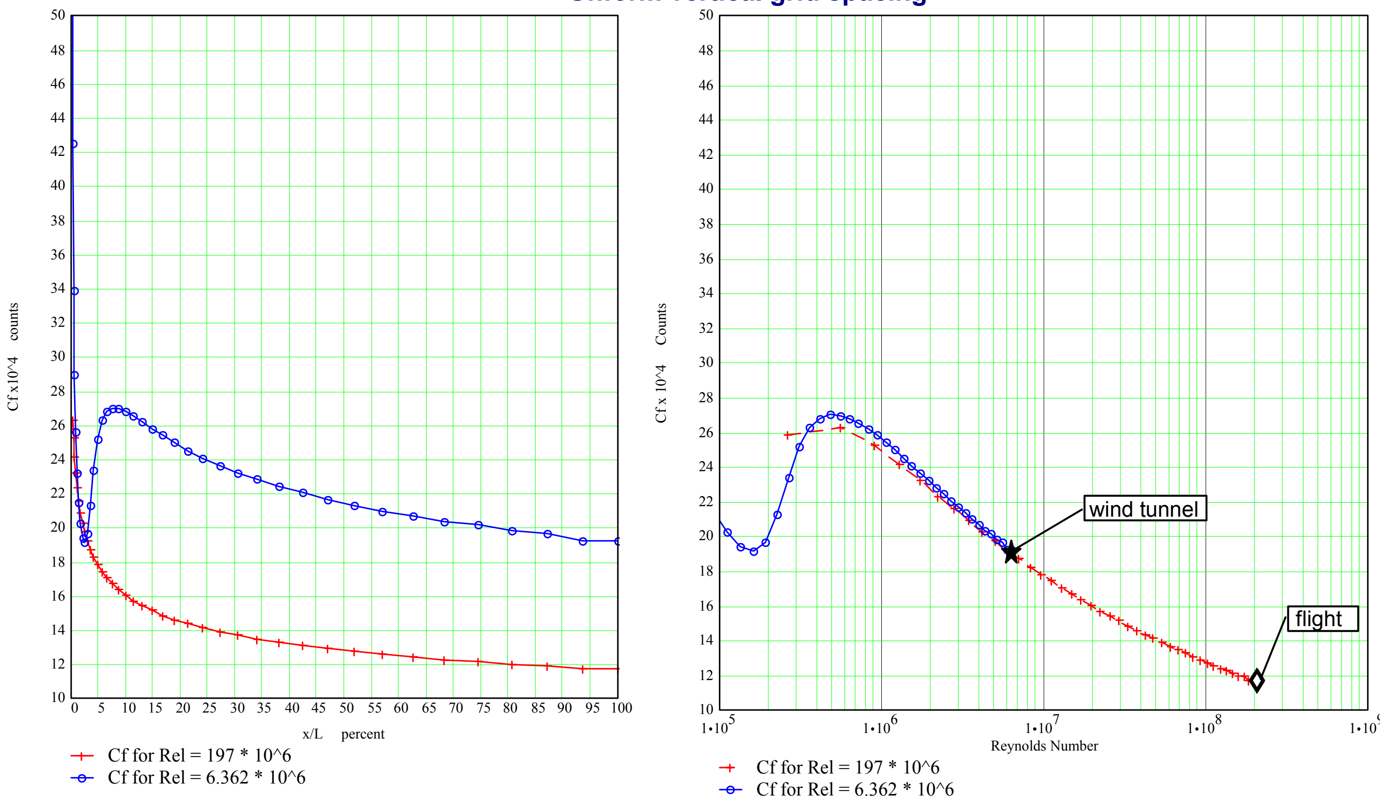


The local skin friction coefficients calculated with the Spalart - Allmaras turbulence model are shown in this figure. At the low local Reynolds the skin friction looks similar to transition from laminar to turbulent flow. This is associated with the nature of the turbulence model characteristics.

BCA OVERFLOW Local Skin Friction Calculations, Cf

Mach = 2.4: Spalart - Allmaras Turbulence Model

Unform vertical grid spacing

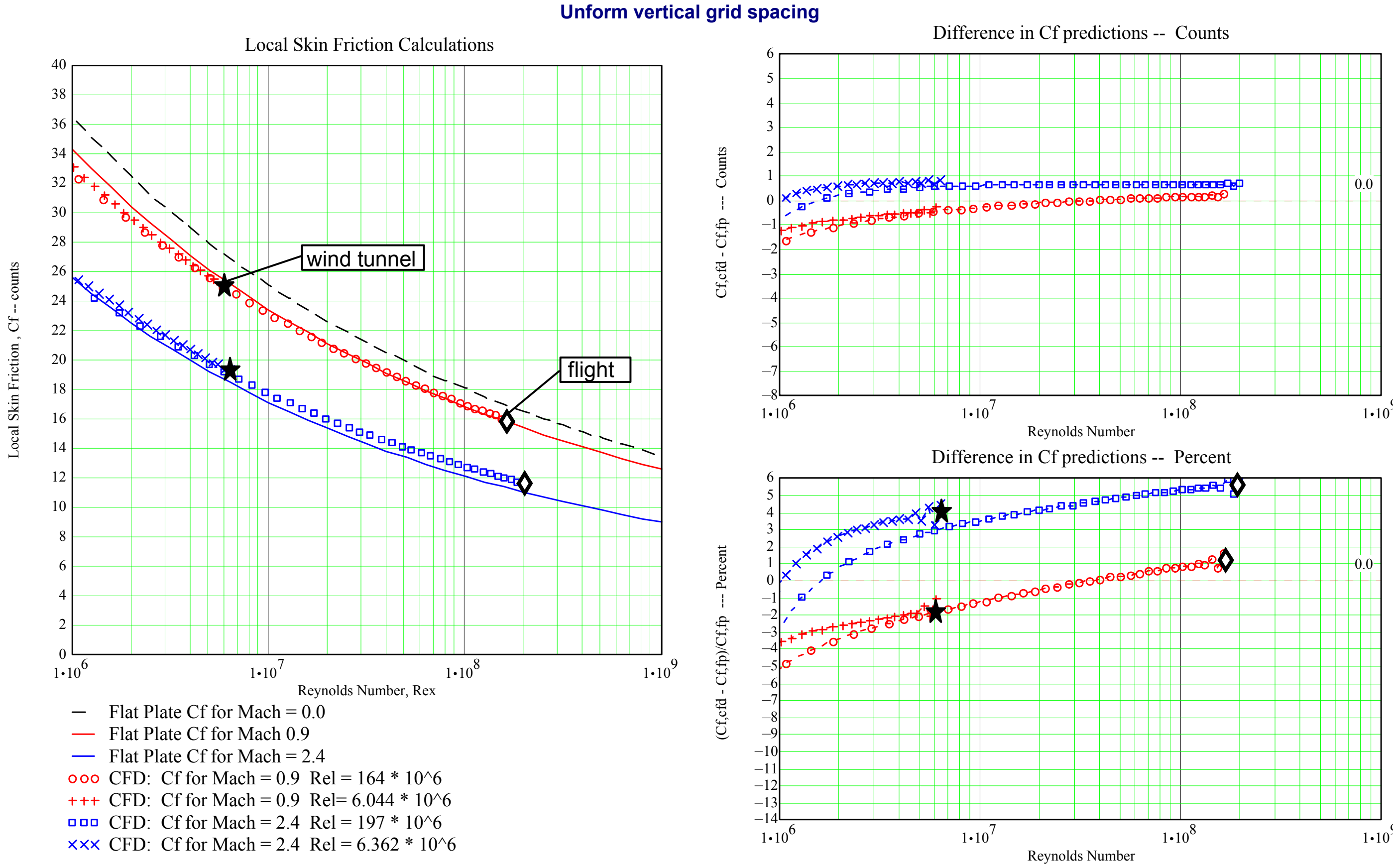


The local Skin Friction Calculations at the lowest Reynolds number again show the pseudo laminar to turbulent transitional flow characteristics.

BCA OVERFLOW Local Skin friction Calculations Comparisons with Flat Plate Cf

Spalart - Allmaras Turbulence Model

Unform vertical grid spacing

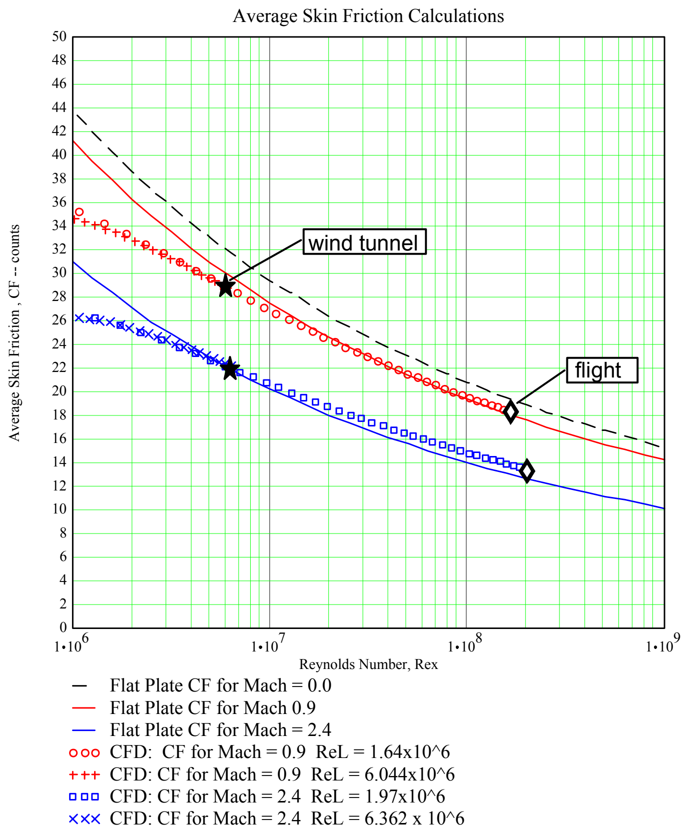


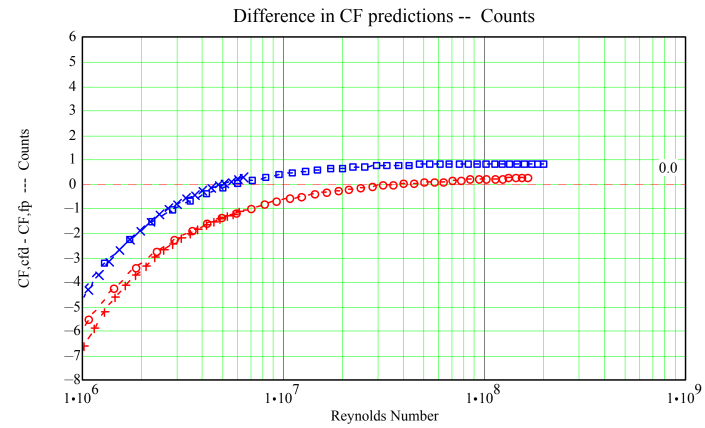
The local skin friction calculated with the Spalart - Allmaras turbulence model is compared with the flat plate theory in this figure. At Mach 0.9, the CFD predictions vary from - 2 % to +1% of the flat plate theory over the wind tunnel to flight Reynolds number range. At Mach 2.4, the CFD predictions are from 4% to 5.5% higher then the flat plate predictions.

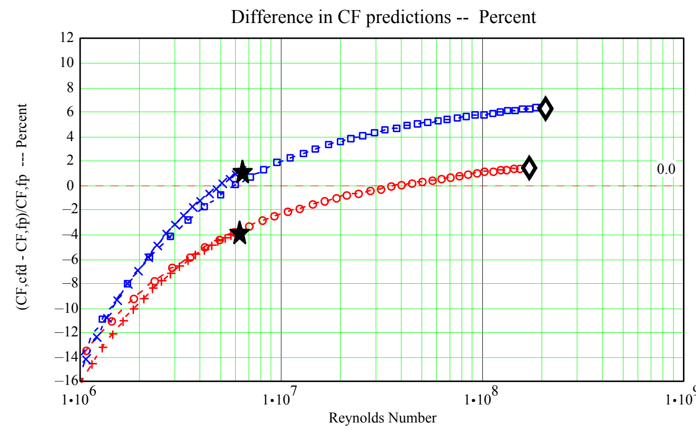
BAC OVERFLOW Average Skin friction Calculations Comparisons with Flat Plate CF

Spalart - Allmaras Turbulence Model

Unform vertical grid spacing





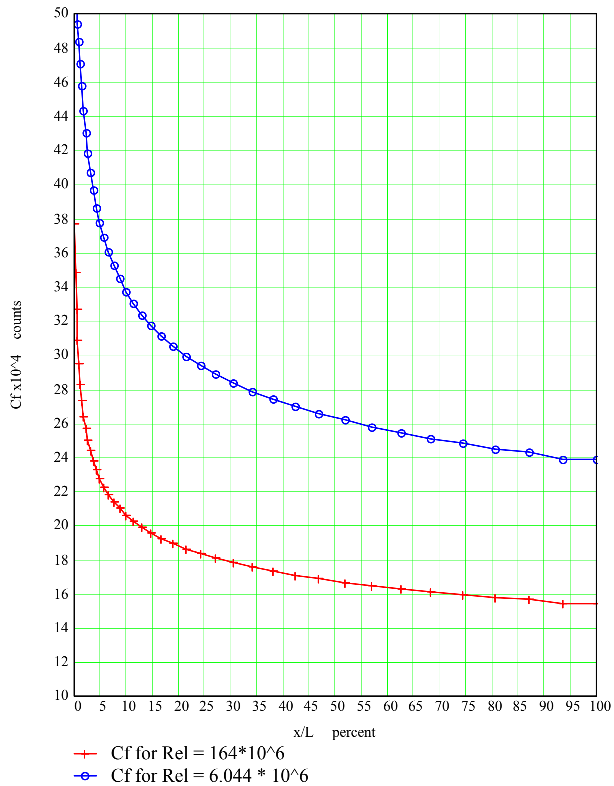


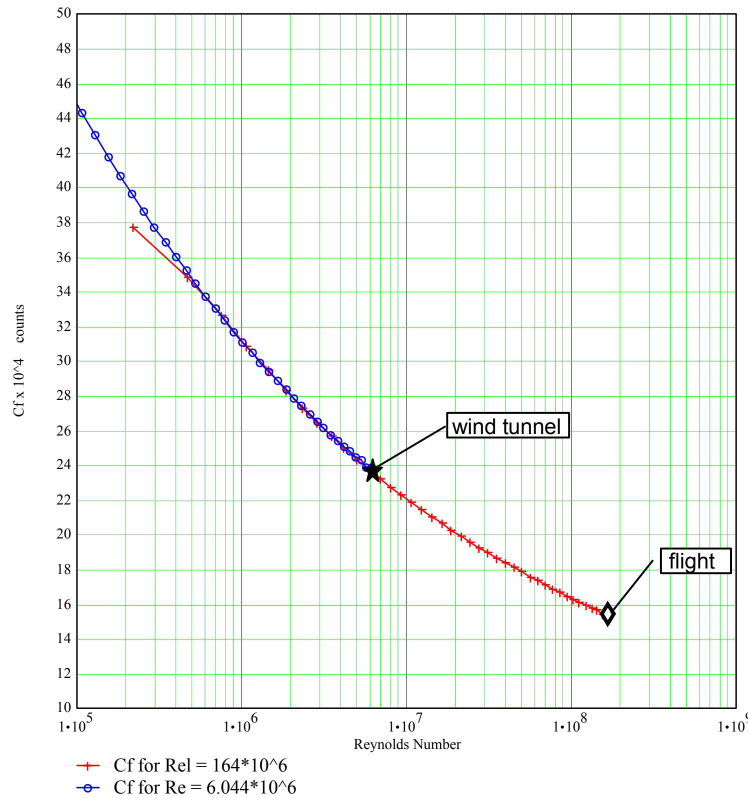
The differences between the CFD predictions of the average skin friction and the flat plate theory varies significantly with Reynolds number. The CFD predictions at the lowest Reynolds numbers fall far below the flat plate theory. This is due to the pseudo transitional flow inherent in the Spalart - Allmaras turbulence model.

BCA OVERFLOW Local Skin Friction Calculations, Cf

Mach = 0.9: Menter's Turbulence Model

Unform vertical grid spacing



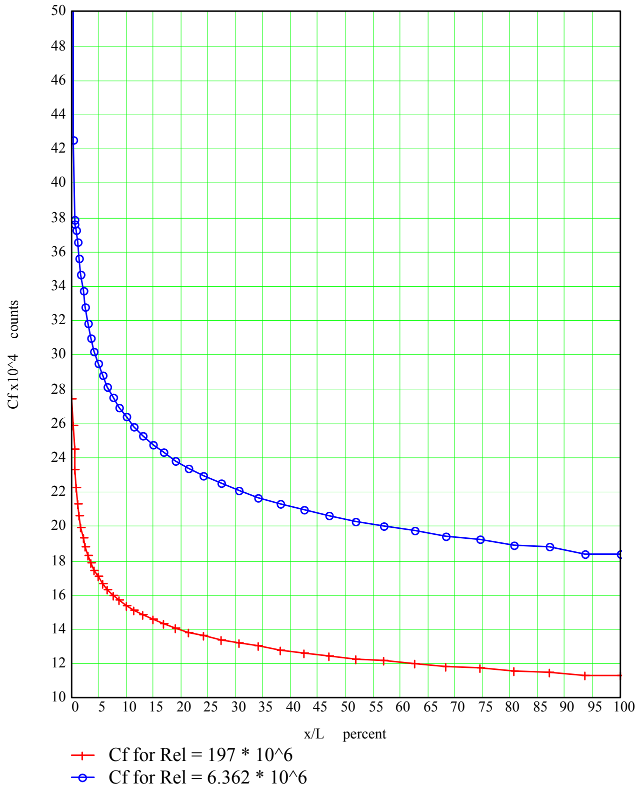


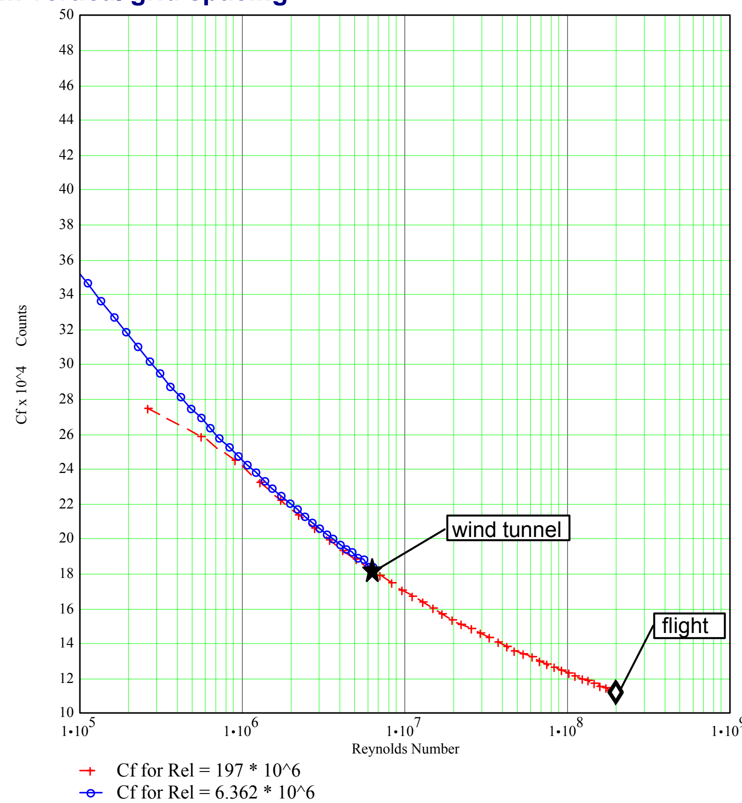
This again shows the local skin friction calculations for both wind tunnel and flight Reynolds numbers. These results were obtained at Mach 0.9 using the Menter's SST turbulence model.

BCA OVERFLOW Local Skin Friction Calculations, Cf

Mach = 2.4: Menter's Turbulence Model

Unform vertical grid spacing



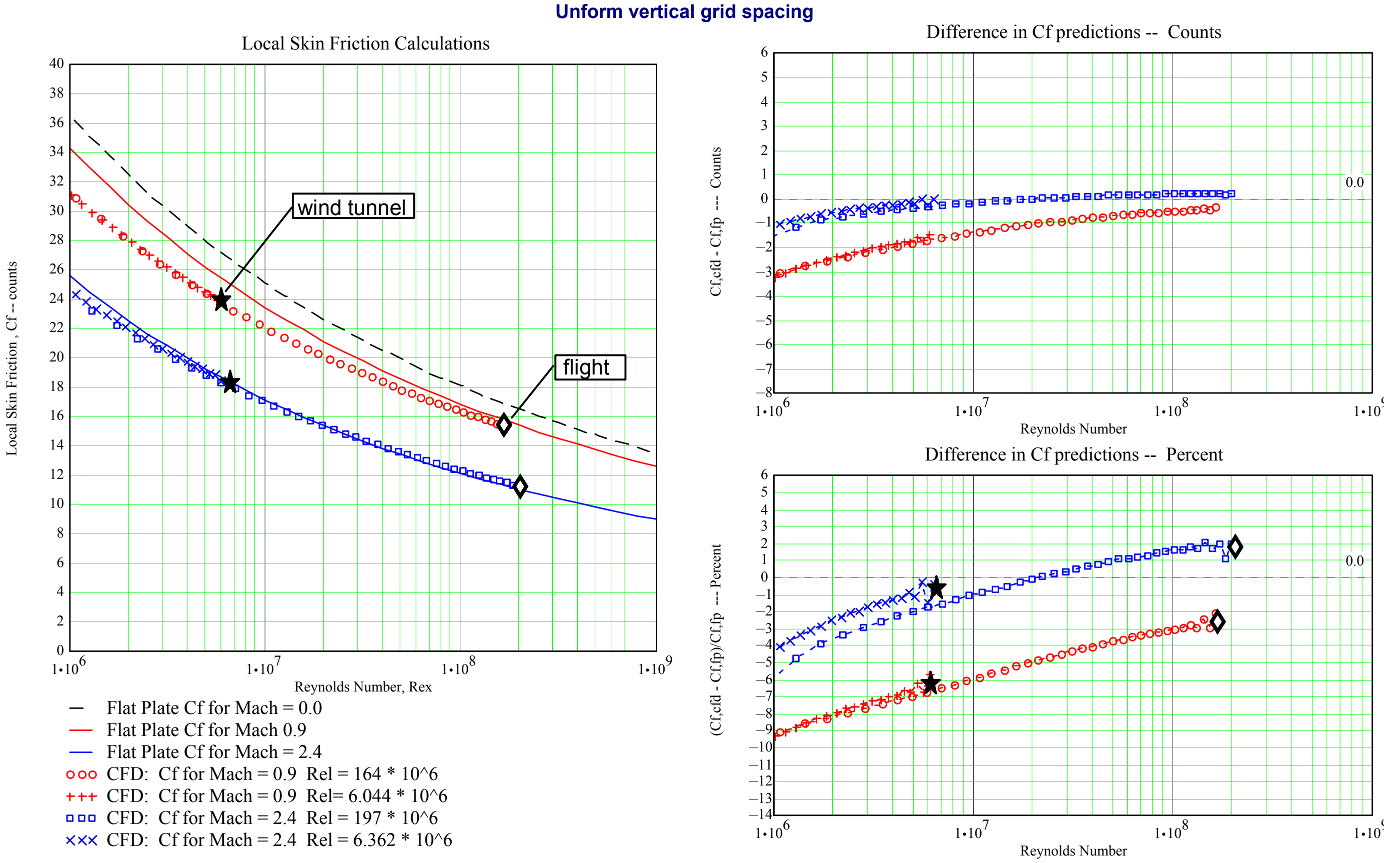


This compares the results obtained with the Menter's SST turbulence models at Mach 2.4 for the wind tunnel and the full scale conditions. The high and the low Reynolds number calculations match closely except for the first 1/2% of the distance from the leading edge of the flat plate for the full scale conditions. The relative grid definition is rather course in that region, but has little effect further aft on the flat plate.

BCA OVERFLOW Local Skin friction Calculations Comparisons with Flat Plate Cf

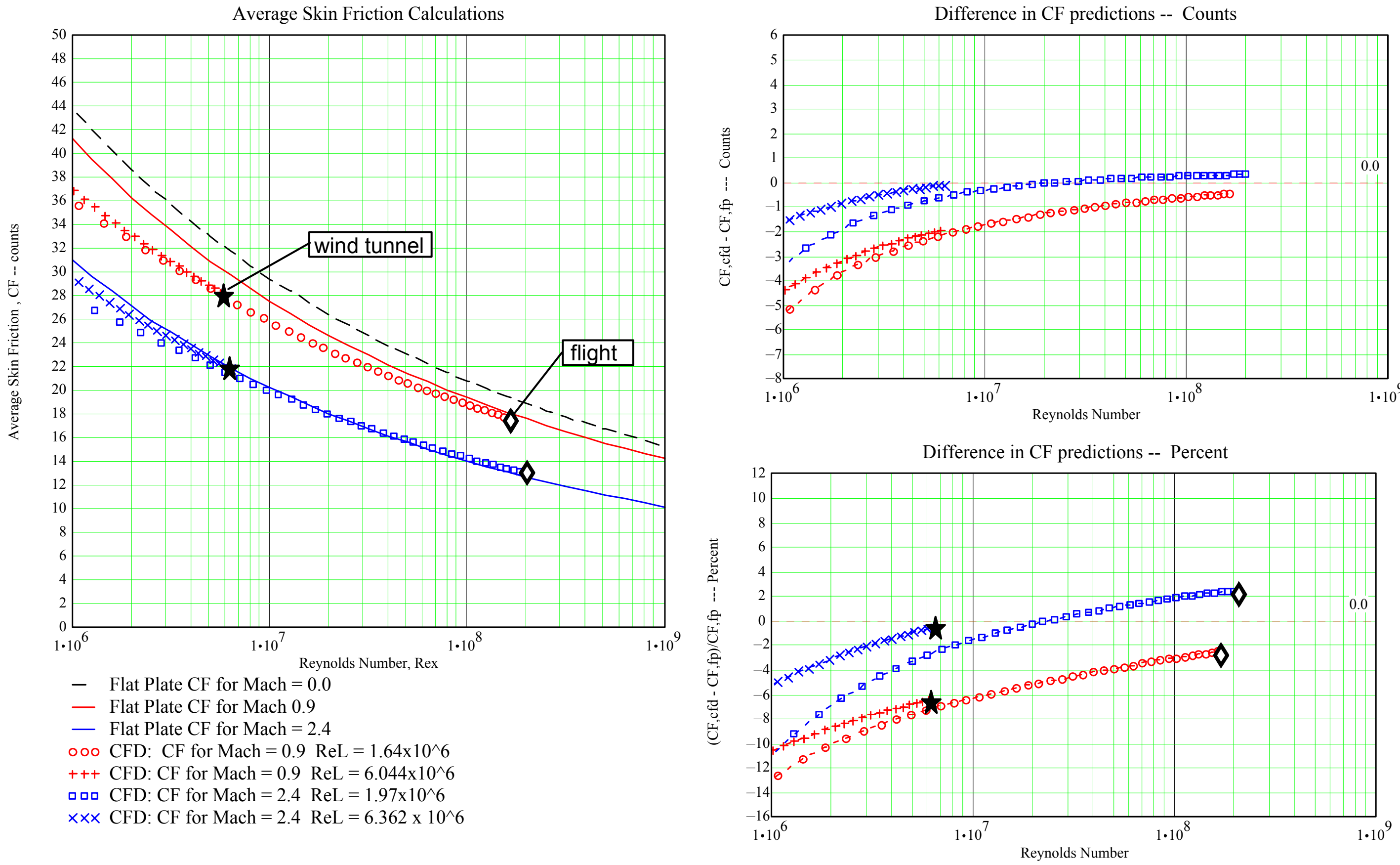
Menter's Turbulence Model

Unform vertical grid spacing



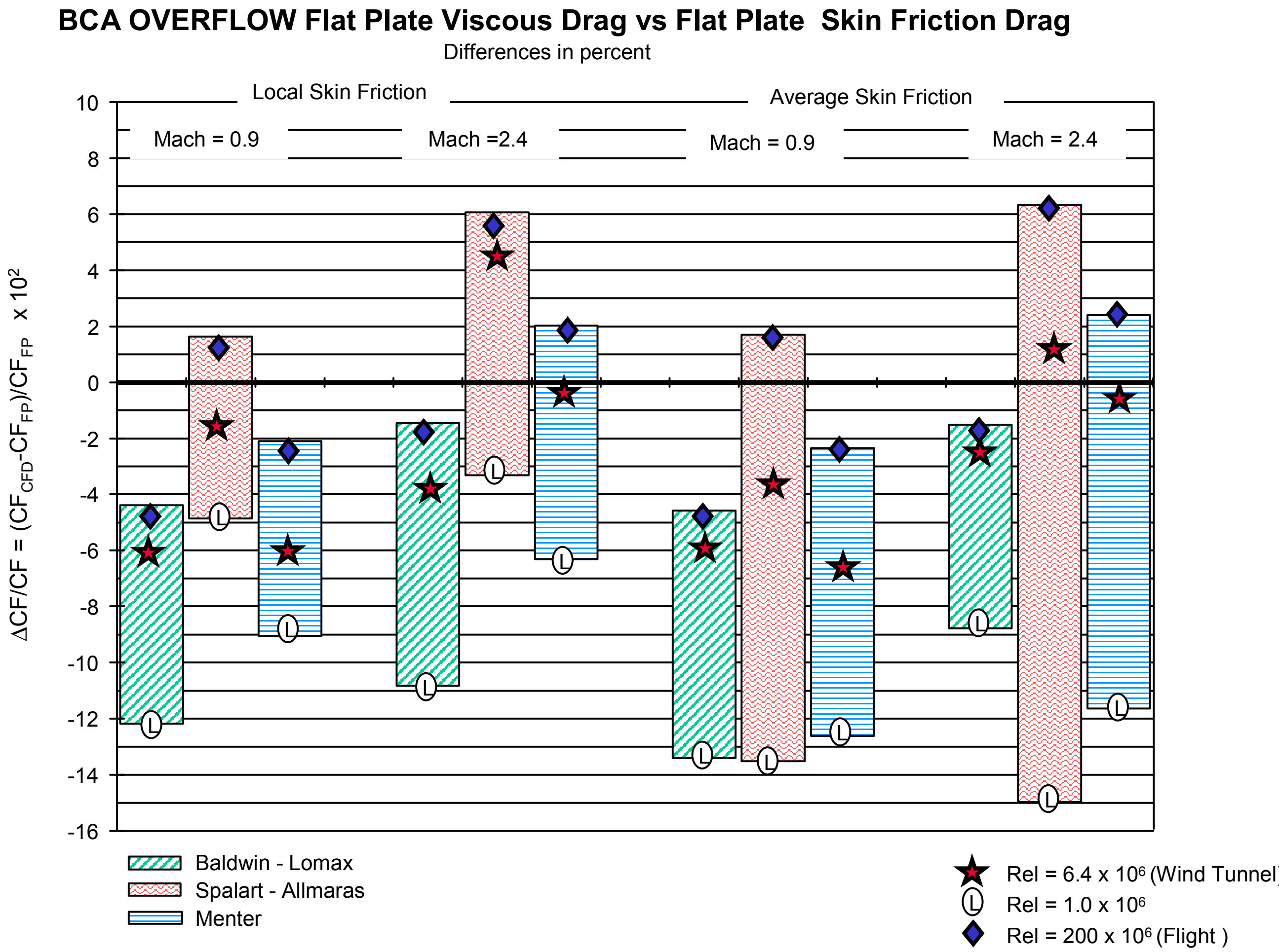
The CFD predictions of local skin friction is far below the flat plate theory for Mach 0.9. The Mach 2.4 predictions are within -1% to +2% of the flat plate theory over the wind tunnel to the flight range of Reynolds numbers. The Variation of Cf with Reynolds computed with the CFD is quite a bit different then the flat plate theory.

BAC OVERFLOW Average Skin friction Calculations Comparisons with Flat Plate CF
Menter's Turbulence Model
Unform vertical grid spacing

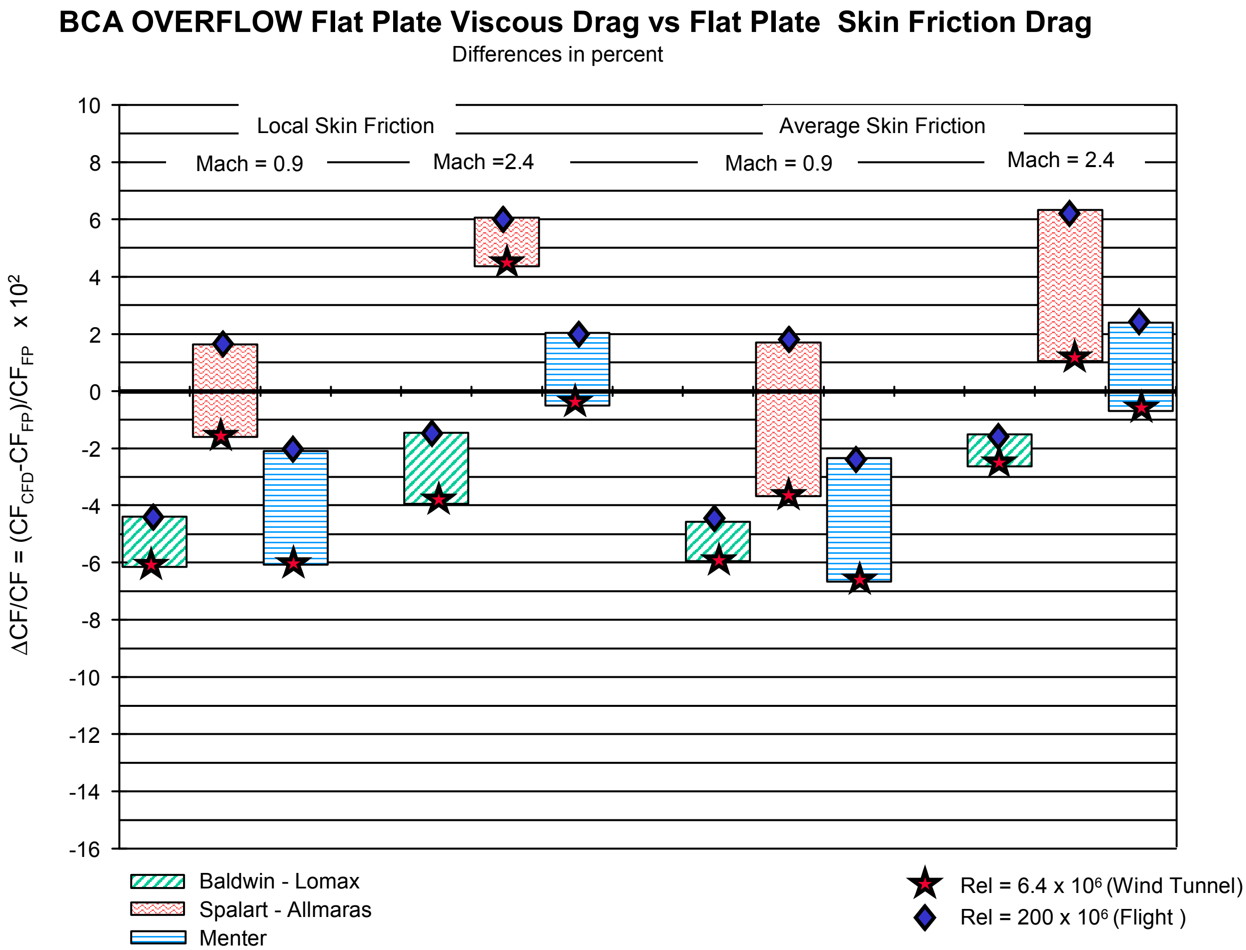


These are comparisons of the average skin friction calculated using the Menter's SST turbulence model with the corresponding flat plate theory calculations.

Over the range of Reynolds from wind tunnel to flight, the CFD predictions at Mach 0.9 are 7 % to 3% lower then the flat plate theory. The Mach 2.4 predictions for the same range of Reynolds numbers vary from - 2% to +2% of the flat plate values



This summarizes the comparisons of the CFD predictions of both local and average skin friction with the corresponding flat plate theory predictions. The greatest differences for each of the comparisons occurs at very low Reynolds number which are not really of interest for HSCT applications.

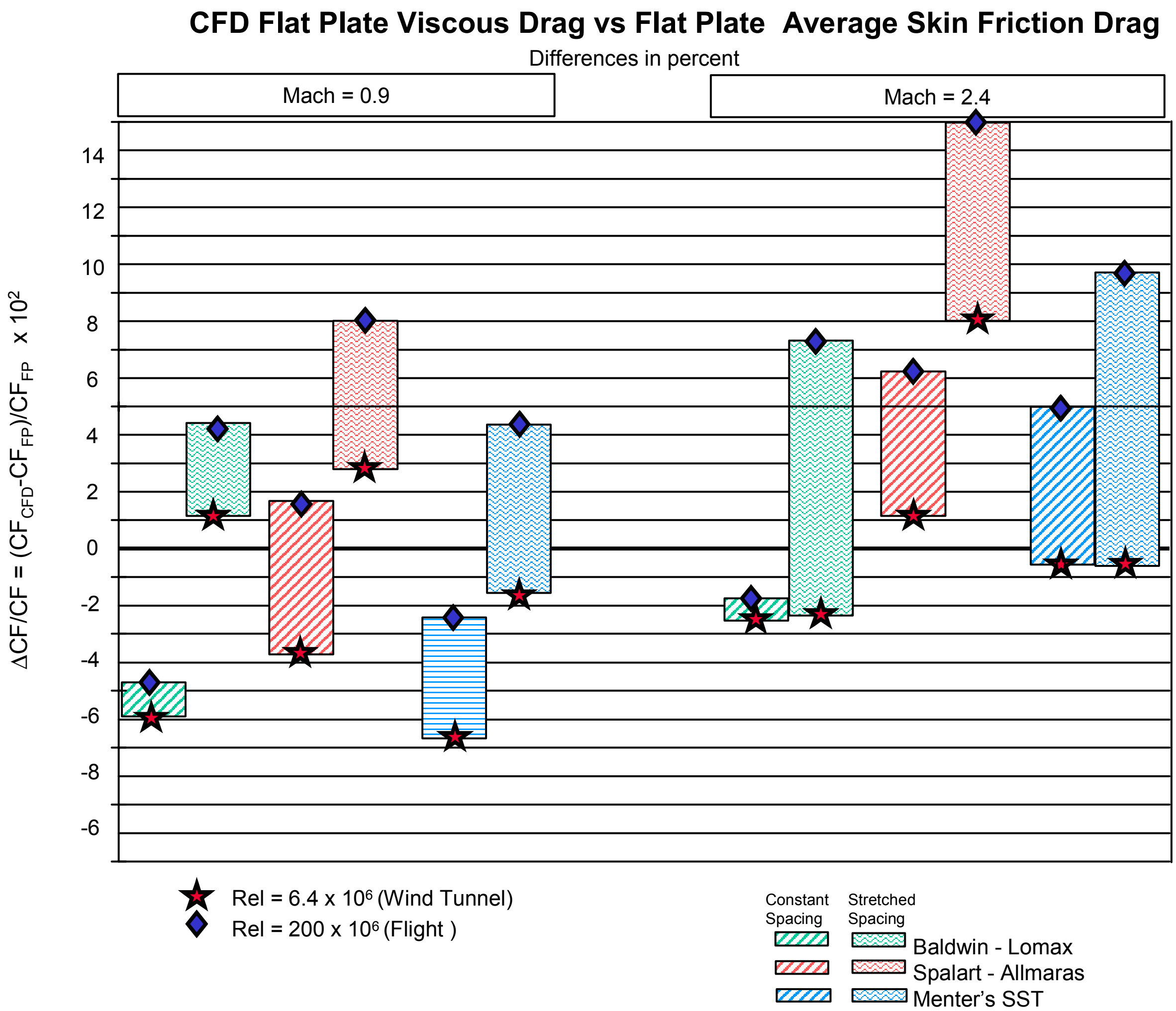


The percentage errors in the OVERFLOW calculations are shown here with the low Reynolds number results removed. The height of each data bar indicates the variation in the OVERFLOW predicted Reynolds number trends as compared to the flat plate predictions.

The Baldwin -Lomax predictions are a nearly constant percent difference less then the flat plate theory depending on the Mach number.

The Average and local skin friction errors for the Spalart - Allmaras calculations, are about equal at flight Reynolds numbers. The error for the average skin friction is greater than that for the local skin friction since the average friction coefficient is affected more by the pseudo laminar flow in wind tunnel Reynolds numbers.

The Menter Calculations are the closest to the flat plate predictions at Mach 2.4 of all the turbulence models. The Mach 0.9 predictions are however, a few percent low.



The OVERFLOW results presented thus far were all calculated using a constant vertical grid spacing. Results obtained using a more conventional stretched grid vertical spacing are compared with the constant grid spacing result in this figure.

The CFD perdictions are seen to be very dependent on the vertical grid spacing scheme. The constant grid spacing predictions agree much better with the flat plate theory then the stretched grid spacing predictions.

ARC Analyses

Code: OVERFLOW

Local Skin Friction, Cf

Average Skin Friction, CF

Turbulence Models:

* Spalart - Allmaras
* Menter's SST

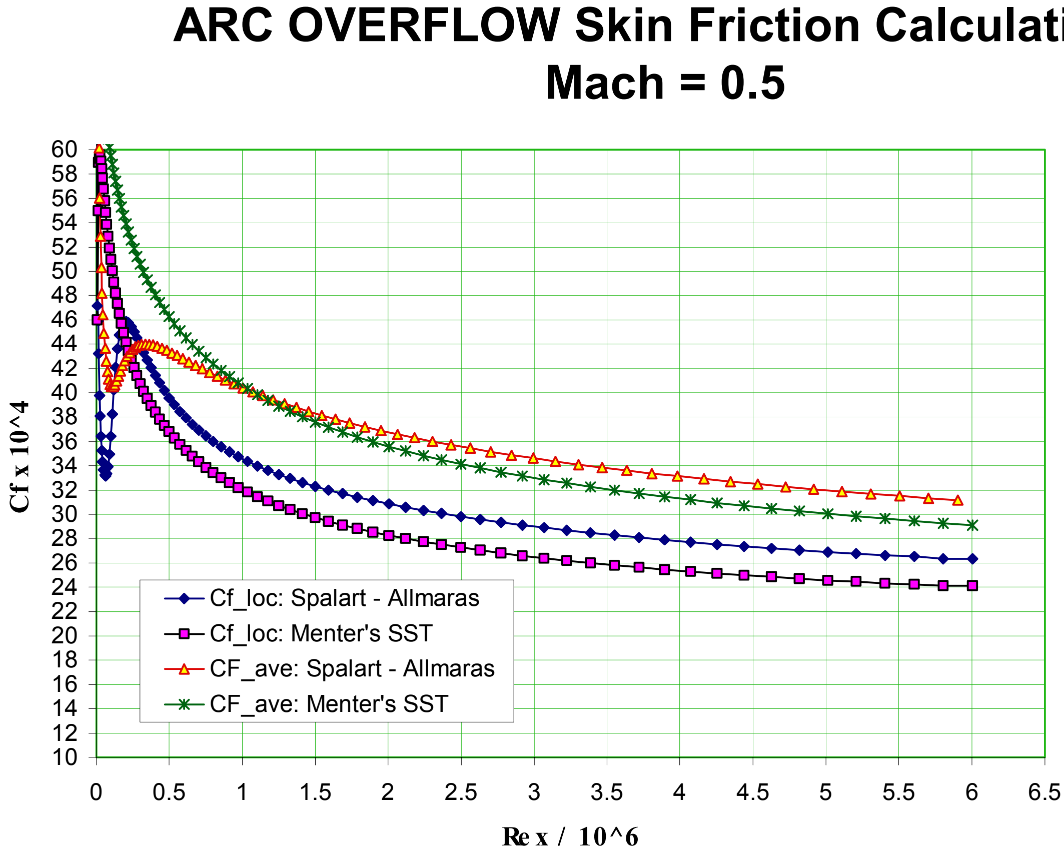
Mach Numbers:

* 0.5
* 0.9
* 1.5
* 2.0
* 2.4

Reynolds Number:

* 10^5 to 6×10^6
* 10^5 to 200×10^8

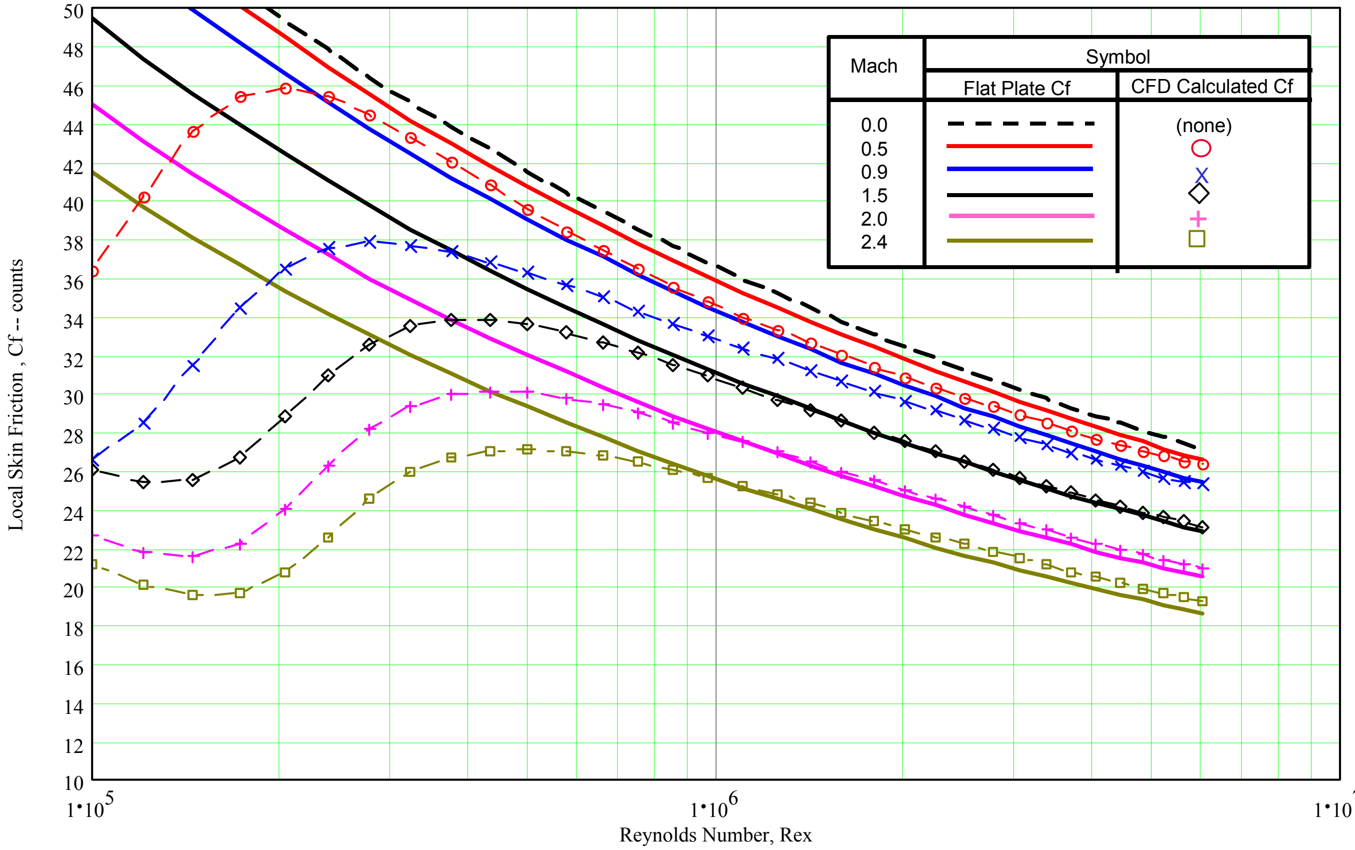
The fully turbulent flow flat plate skin friction calculations made by NASA Ames were obtained using the OVERFLOW program with two different turbulence models.
Most of the calculations were made at wind tunnel Reynolds number. These included a range of Mach numbers from 0.5 to 2.4
At Mach 2.4 additional full scale Reynolds nimber calculations were made.



This chart shows a comparison of the local and average skin friction calculations obtained with the Spalart - Allmaras turbulence model and with the Menter's SST turbulence model. The Spalart - Allamras results again show a pseudo laminar flow to turbulent flow transitional characteristic. At wind tunnel Reynolds Numbers the skin friction predictions are quite a bit different for the two sets of calculations.

Nasa Ames OVERFLOW Local Cf Calculations Comparisons with Flat Plate Cf

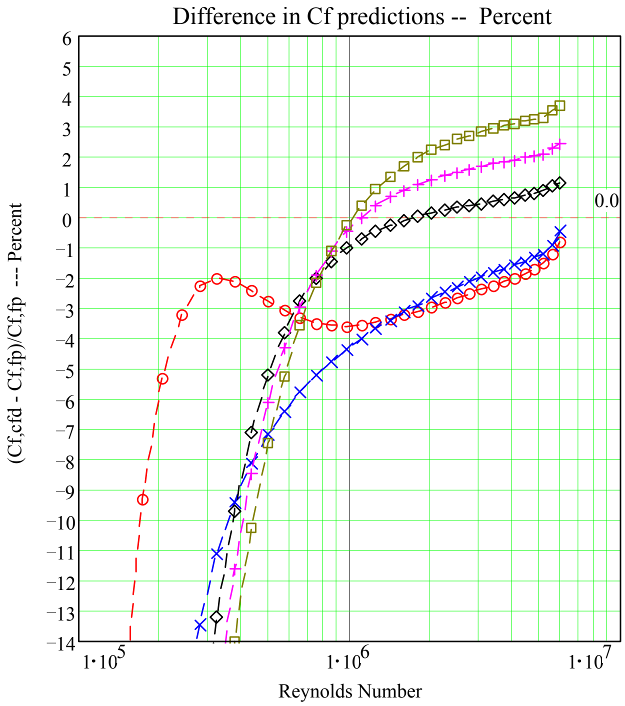
- Spalart - Allmaras Turbulence Model
- NASA Ames OVERFLOW Code
- Wind Tunnel Reynolds Number

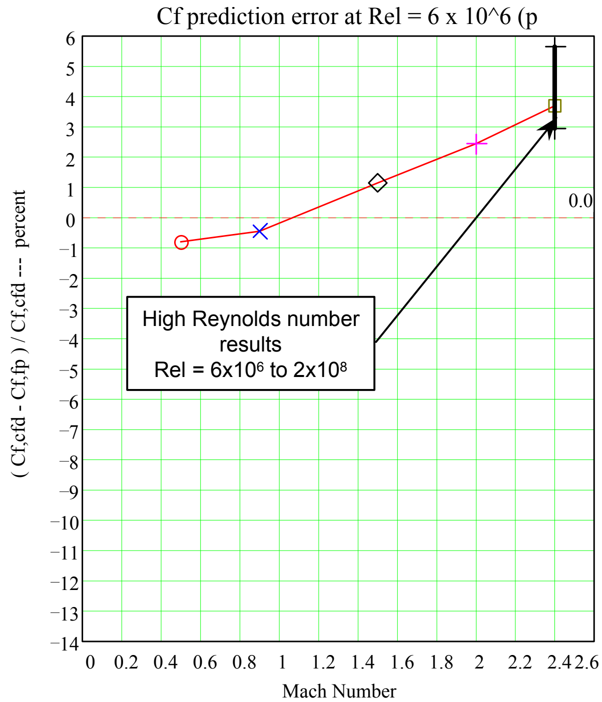


This is a comparison of the local skin friction calculations using the Spalart - Allmaras turbulence model versus the corresponding flat plate theory calculations. Calculations were made for range of Mach numbers from 0.5 to 2.4. At the low Reynolds numbers , as a result of the pseudo laminar / transitional flow calculations within the Spalart - Allmaras turbulence model, the CFD predictions fall below the flat plate theory. At the highest Reynolds Numbers, local skin friction CFD calculations are slightly less than the flat plate values at low Mach numbers At the higher Mach numbers, CFD predictions tended to exceed the flat plate theory values.

Differences Between CFD Calculated Cf and Flat Plate Cf

- Spalart - Allmaras Turbulence Model
- NASA Ames OVERFLOW Code
- Wind Tunnel Reynolds Number

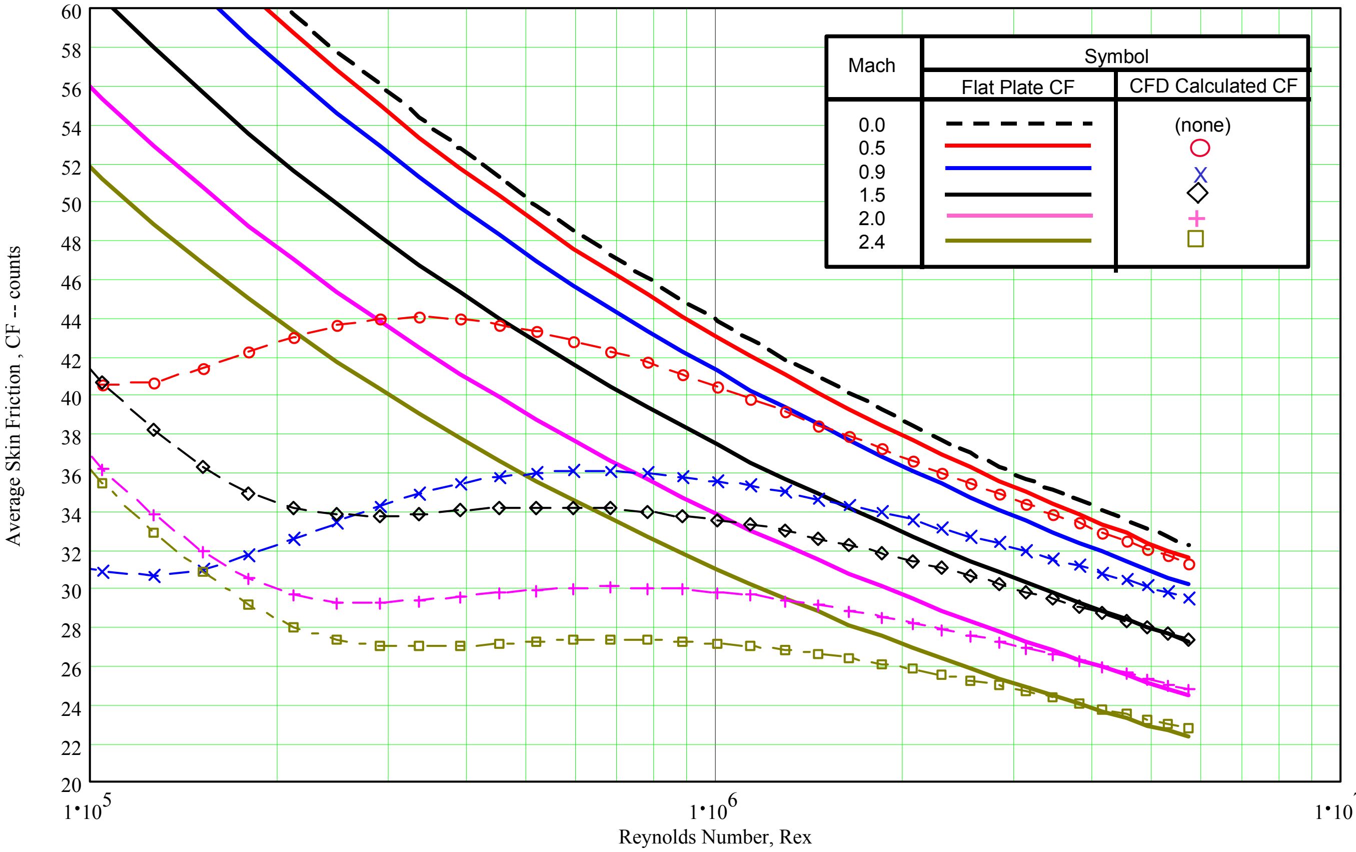




This shows the differences between the CFD and the flat plate predictions of local skin friction drag as a percentage difference relative to the flat plate theory. At wind tunnel Reynolds numbers (approximately 2 x 10^6) , the CFD predictions differ from the flat -plate theory by approximately minus 1 to plus 3.4% .

Nasa Ames OVERFLOW Average CF Calculations Comparisons with Flat Plate CF

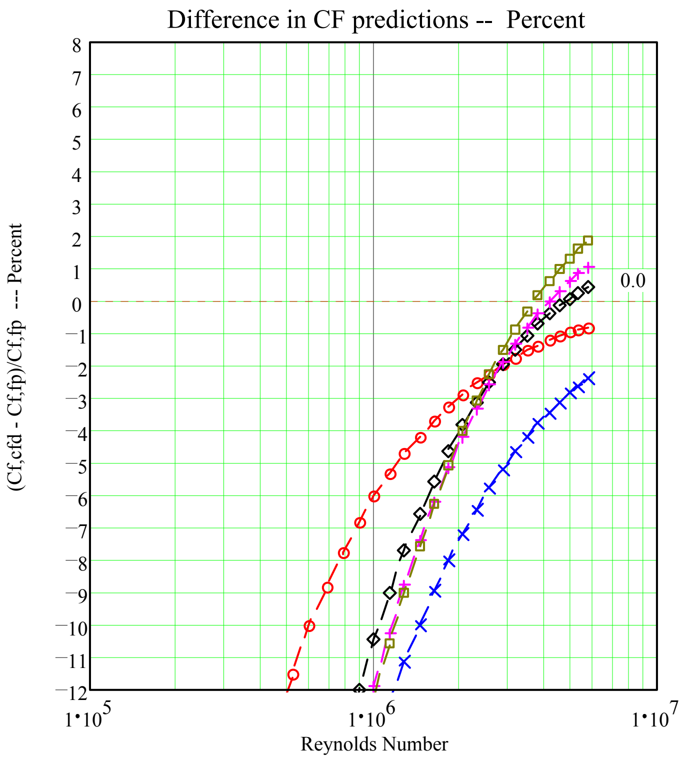
- Spalart - Allmaras Turbulence Model
- NASA Ames OVERFLOW Code
- Wind Tunnel Reynolds Number

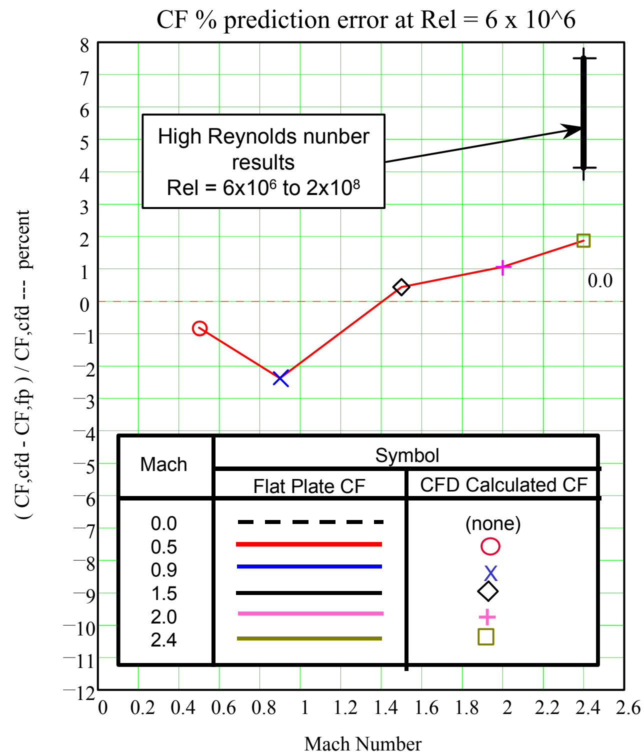


This compares the NASA Ames average skin friction calculations, obtained with the Spalart - Allmaras turbulence model, with the flat plate theory results.. Similiar to the local skin friction results, the CFD average CF predictions are significantly less then the flat plate theory at the lowest Reynolds numbers and tend to match better at wind tunnel Reynolds numbers

Differences Between CFD Calculated CF and Flat Plate CF

- NASA Ames OVERFLOW Code
- Spalart - Allmaras Turbulence Model
- Wind Tunnel Reynolds Number

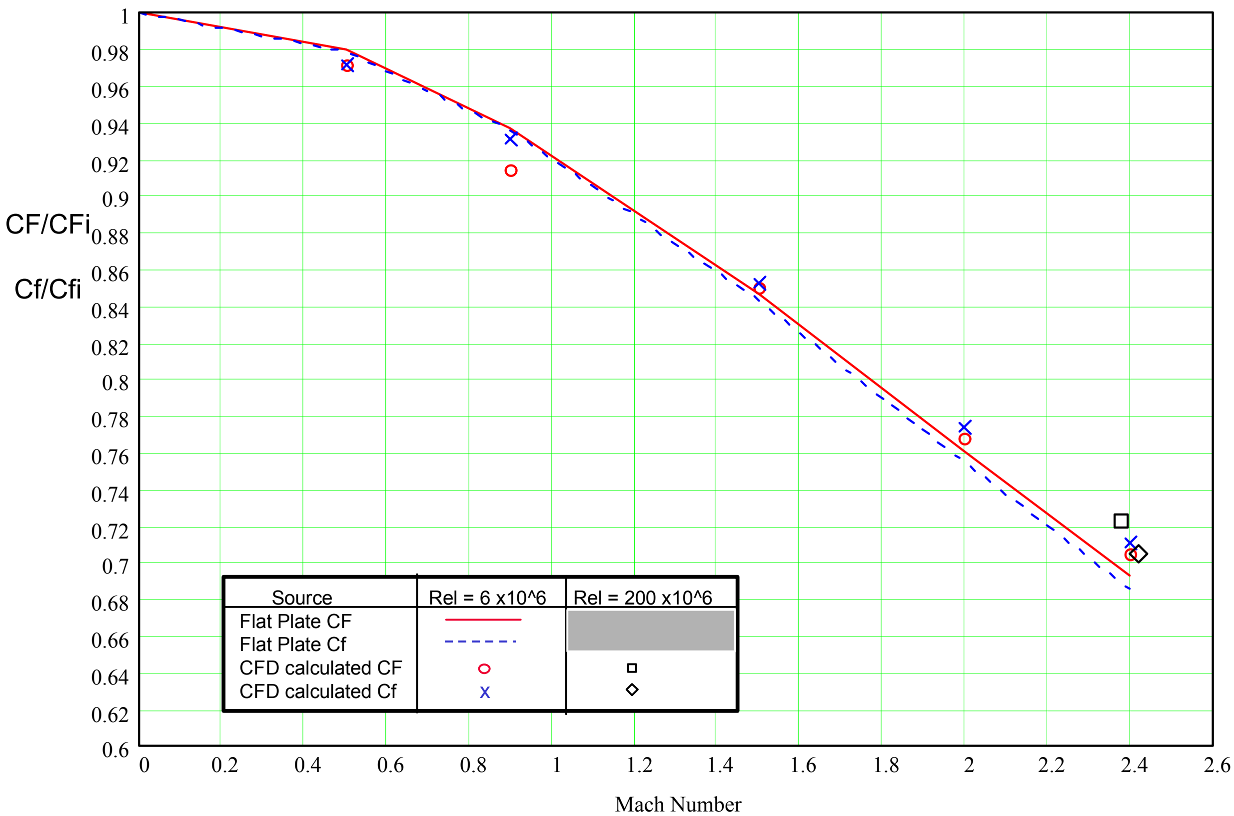




This shows the differences in the CFD and flat plate average skin friction calculations in percent relative to the flat plate theory. At the lowest Reynolds numbers, the CFD predictions are significantly less then the flat plate theory. However, near wind tunnel Reynolds the CFD predictions are within plus and minus 2 % .

Average Skin Friction Calculations: CF /CFi

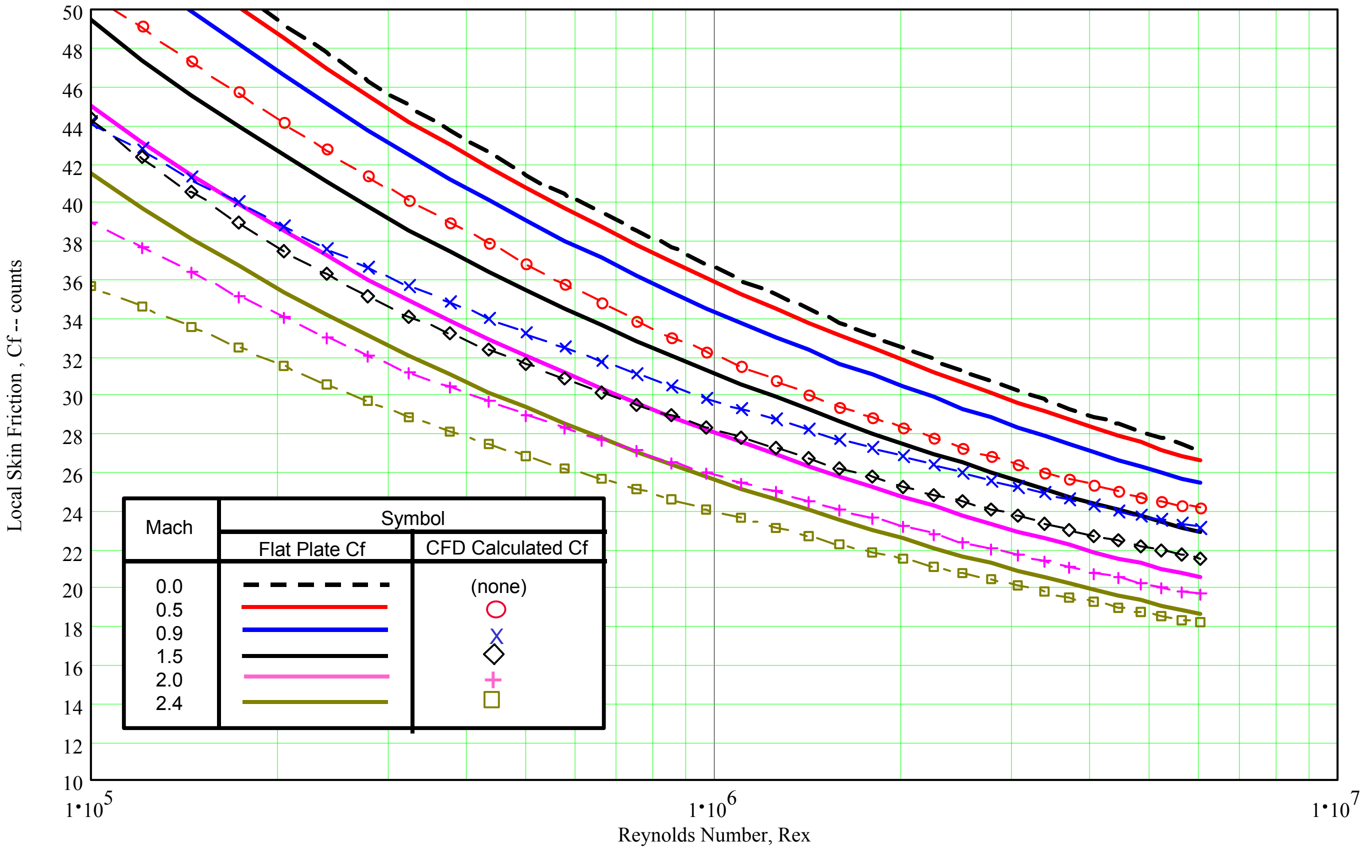
- NASA Ames OVERFLOW Code
- Spalart - Allmaras Turbulence Model



This illustrates the predicted effects of Mach number on both average and local skin friction coefficients. The average and local skin friction coefficients are shown as a ratio to the flat plate incompressible skin friction at the same Reynolds numbers. This tends to eliminate Reynolds number effects in the comparisons. The CFD predictions are slightly less then the flat plate results at the subsonic Mach numbers and slightly higher at the supersonic Mach numbers.

Nasa Ames OVERFLOW Local Cf Calculations Comparisons with Flat Plate Cf

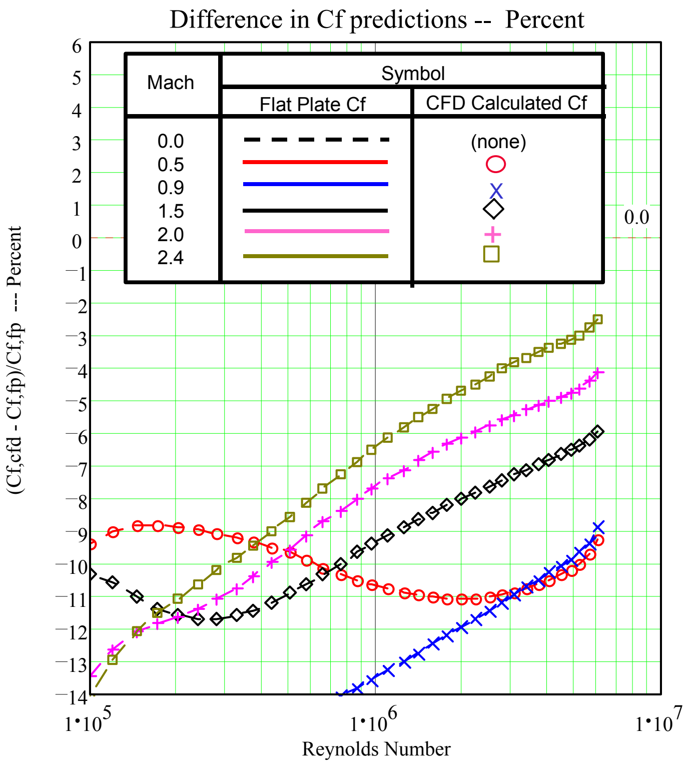
- Menter's SST Turbulence Model
- NASA Ames OVERFLOW Code
- Wind Tunnel Reynolds Number

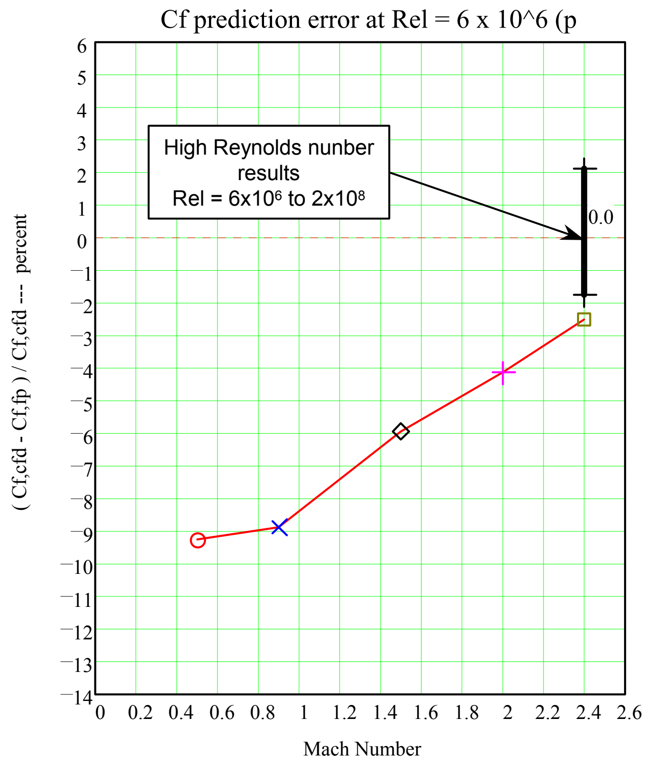


The local skin friction calulated using the Menter's SST turbulence model are compared with the flat theory. The results obtained using the Menter's SST Turbulence model do not show the same pseudo laminar flow effects as the predictions obtained with the Spalart - Allmaras turbulence model. However the predictions all fall below the flat plate theory.

Differences Between CFD Calculated Cf and Flat Plate Cf

- NASA Ames OVERFLOW Code
- Menter's SST Turbulence Model
- Wind Tunnel Reynolds Number

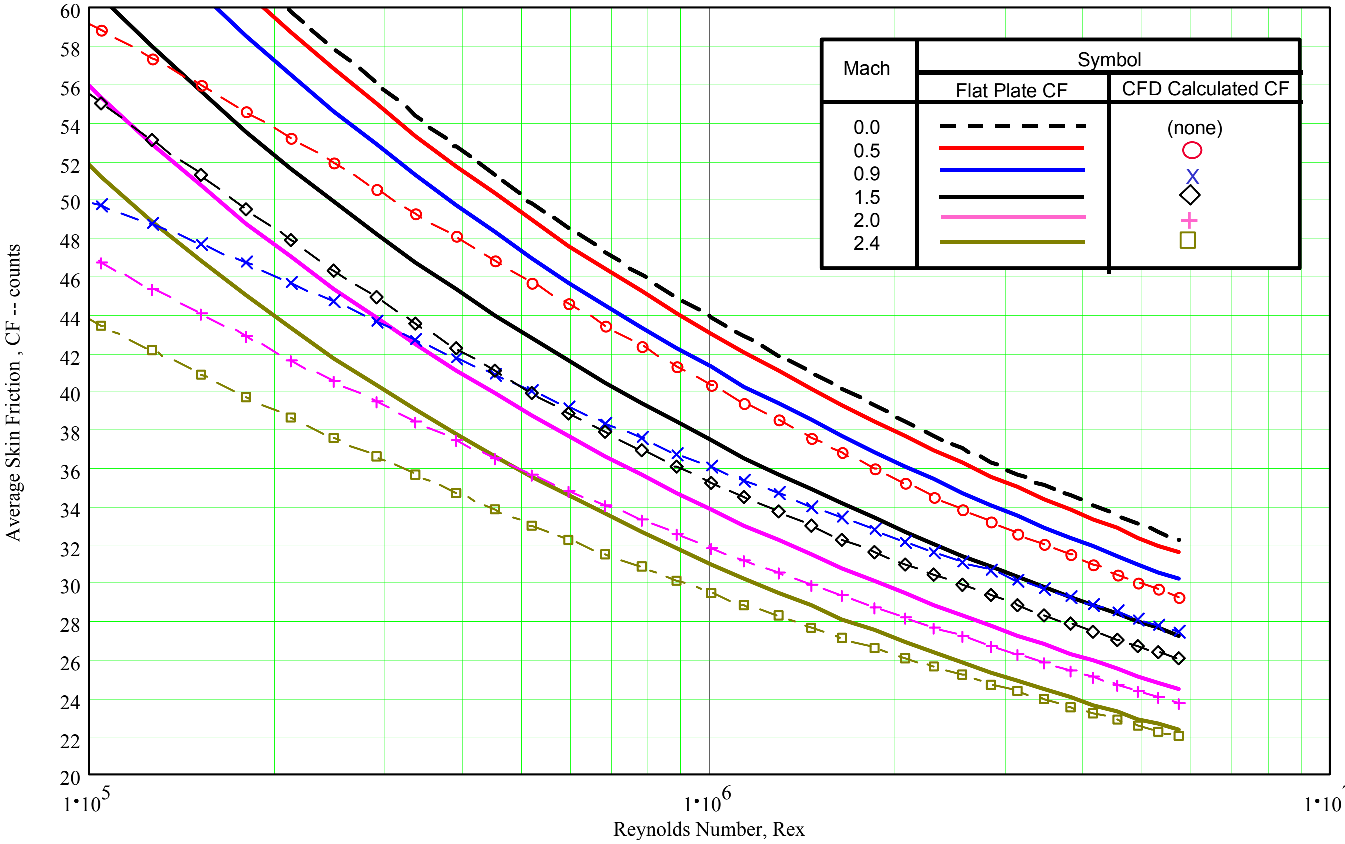




The differences between the CFD and flat plate predictions are shown in percent relative to the flat plate theory. The CFD predictions are significantly less then the flat plate theory at the lower Reynolds numbers. The Mach 2.4 results for wind tunnel to flight Reynolds numbers agree quite well with the flat plate theory.

Nasa Ames OVERFLOW Average CF Calculations Comparisons with Flat Plate CF

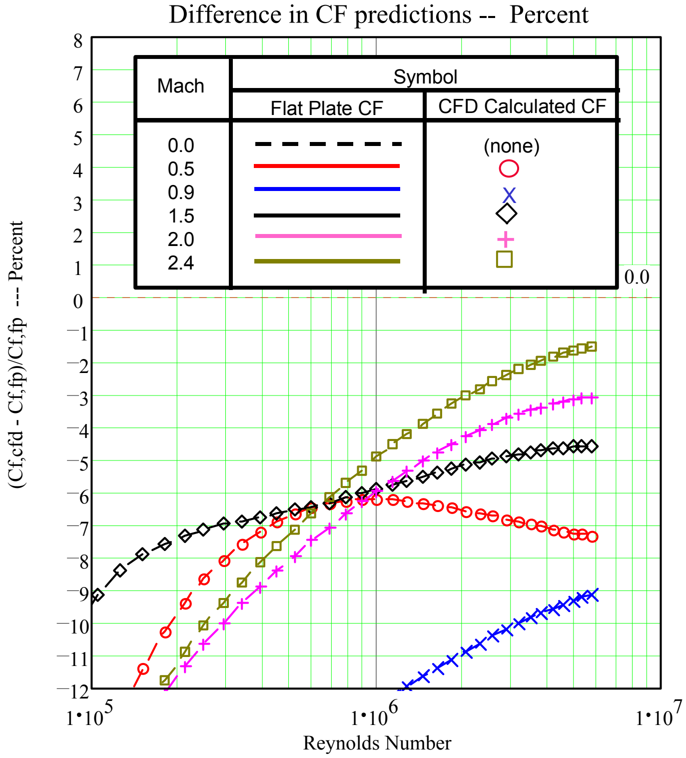
- Menter's SST Turbulence Model
- NASA Ames OVERFLOW Code
- Wind Tunnel Reynolds Number

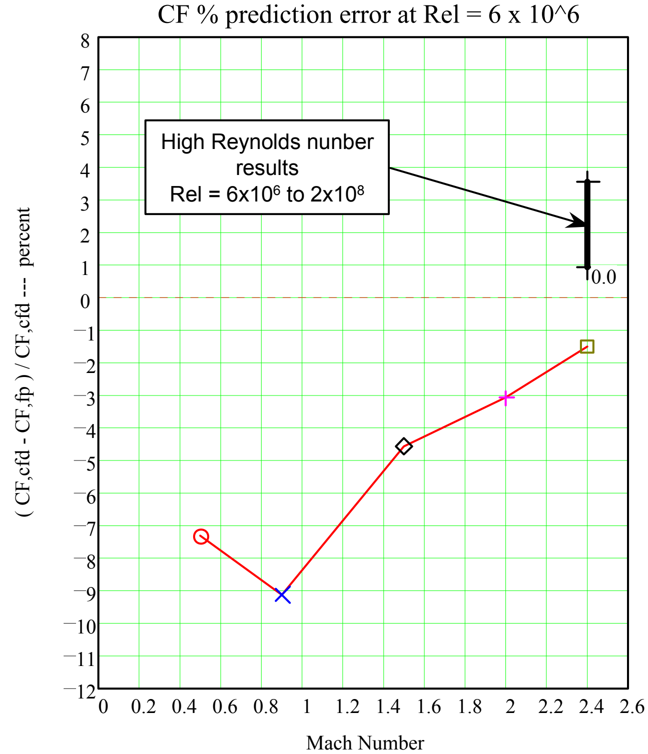


The CFD average skin friction calculations using the Menter's SST turbulence model all fall below the flat plate theory.

Differences Between CFD Calculated CF and Flat Plate CF

- NASA Ames OVERFLOW Code
- Menter's SST Turbulence Model
- Wind Tunnel Reynolds Number

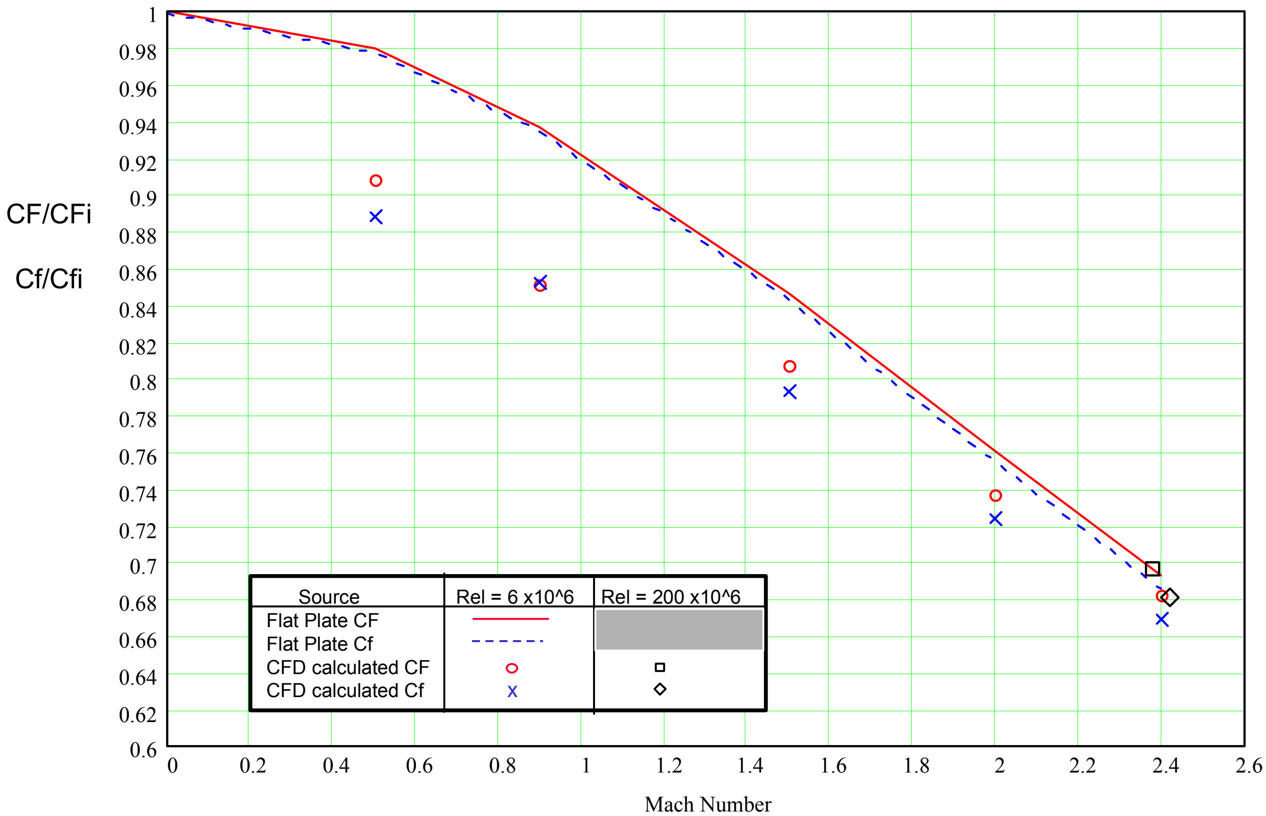




The differences between the CFD average skin friction calculations and the flat plate theory calculations are shown in percent. The CFD predictions are significantly less then the flat plate theory except for Mach 2.4 wind tunnel to flight Reynolds numbers.

Average Skin Friction Calculations: CF /CFi

- NASA Ames OVERFLOW Code
- Menter's SST Turbulence Model
- Wind Tunnel Reynolds Numbers



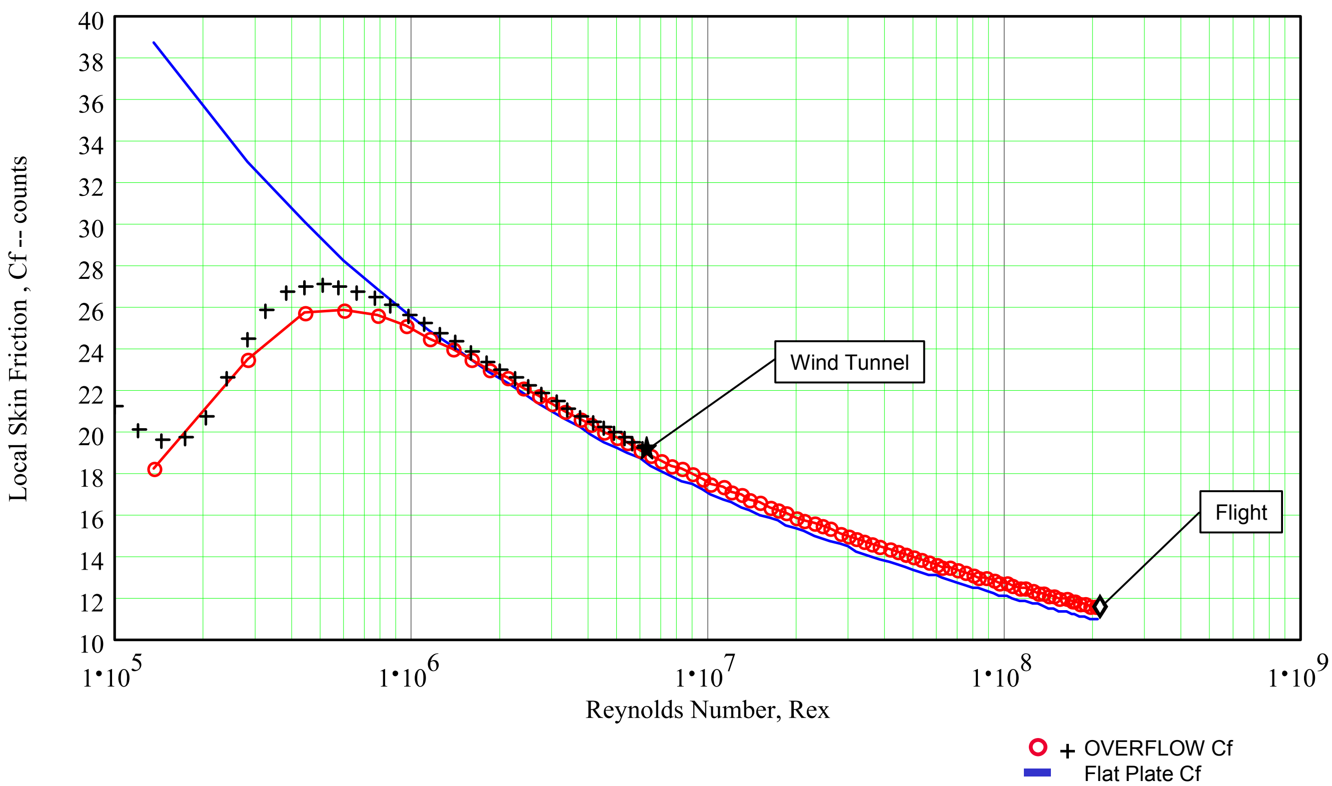
The Average skin friction calculations are shown as a ratio to the flat plate incompressible skin friction at the same reynolds numbers. The predicted Mach number trends are significantly different between the CFD and the flat plate theory results. The highest Mach number results are however quite close to the flat plate theory

Nasa Ames OVERFLOW Local Cf Calculations Comparisons with Flat Plate Cf

Mach = 2.4

Spalart - Allmaras Turbulence Model

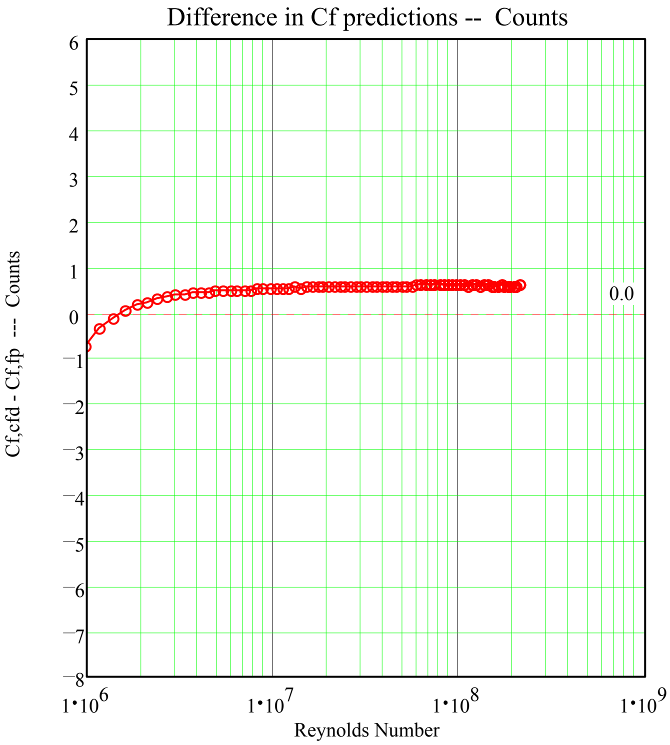
Unform vertical grid spacing

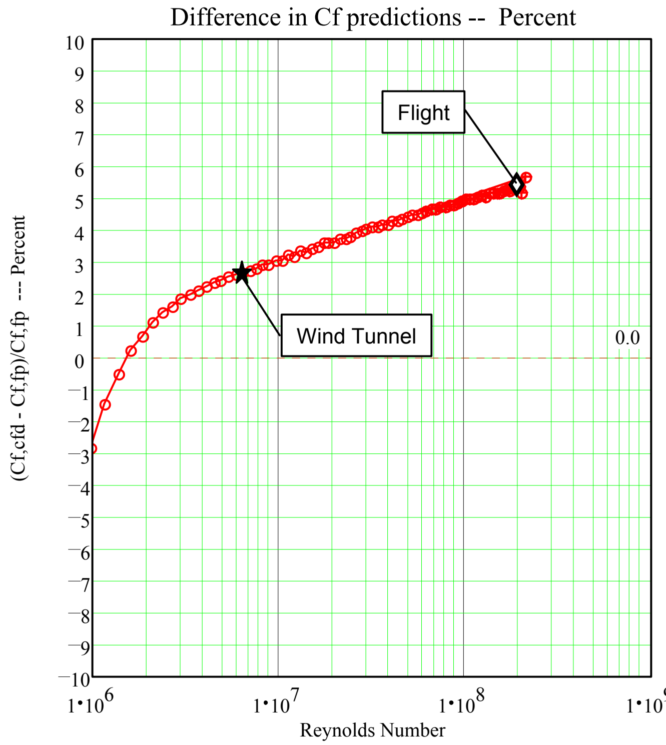


The OVERFLOW calculations by NASA Ames were made for two different overall length Reynolds numbers. One corresponded to a typical wind tunnel condition and one to a flight condition. The distributions of both average and local skin friction with Reynolds numbers were then obtained at different locations along the flat plate for each of the Reynolds numbers. Consequently the most accurate calculation is that at the overall length of the flat plate. This compares the local skin friction distribution with local Reynolds numbers for those two calculation conditions. The local skin friction for the wind tunnel analysis blends quite well into the flight condition results.

Differences Between CFD Calculated Local Cf and Flat Plate Cf

- Mach = 2.4
- NASA Ames OVERFLOW Code
- Spalart - Allmaras Turbulence Model



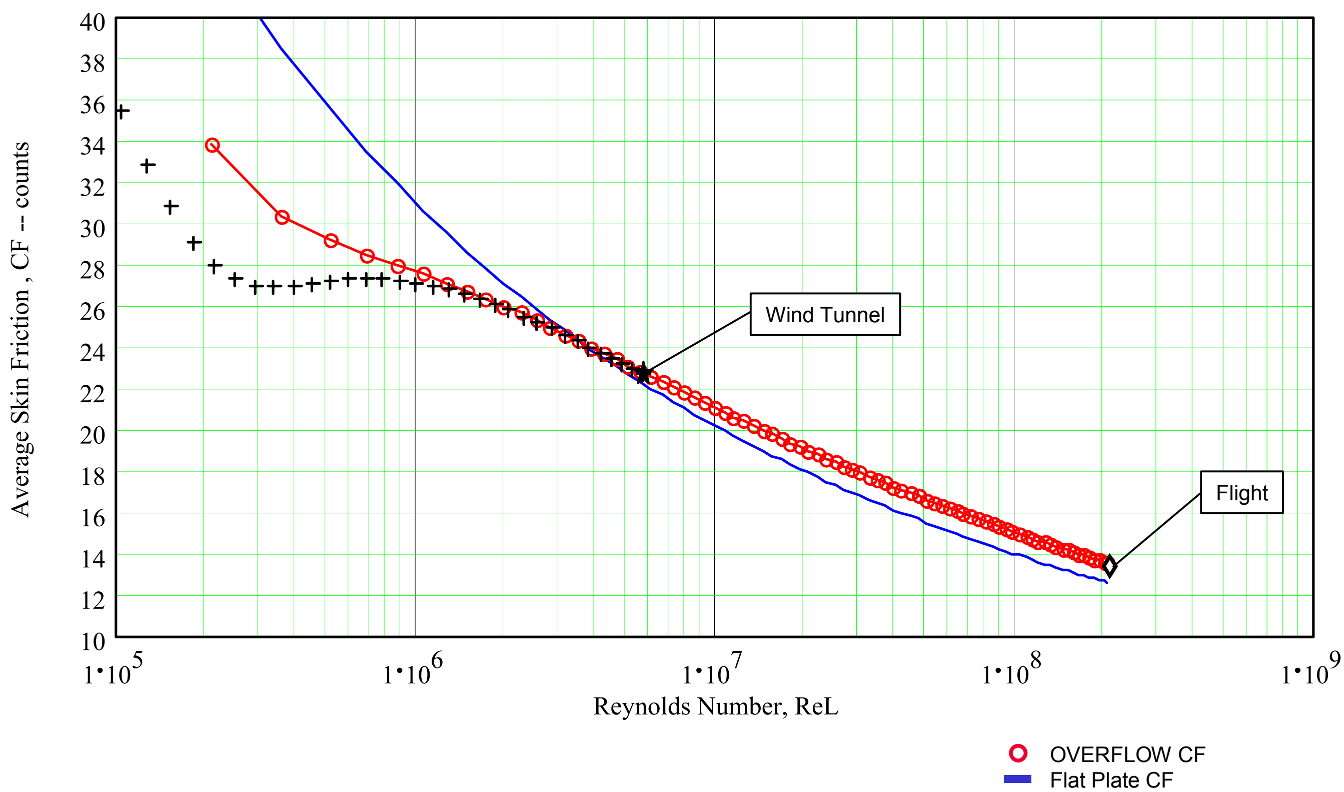


Nasa Ames OVERFLOW Average CF Calculations Comparisons with Flat Plate Cf

Mach = 2.4

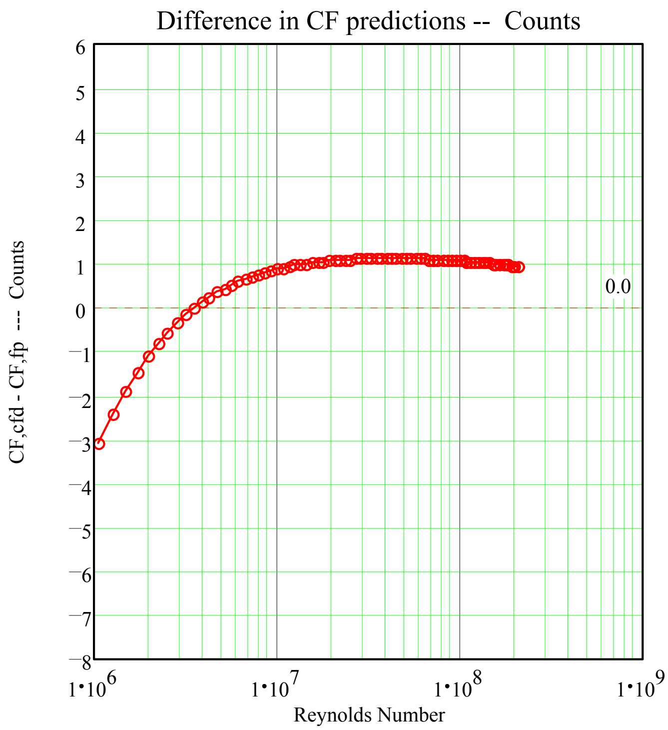
Spalart - Allmaras Turbulence Model

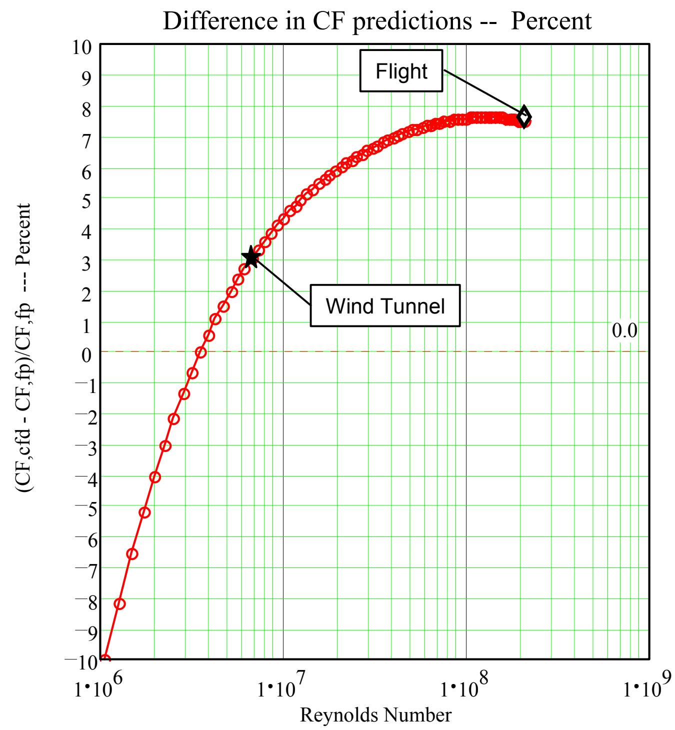
Unform vertical grid spacing



Differences Between CFD Calculated Average CF and Flat Plate CF

- Mach = 2.4
- NASA Ames OVERFLOW Code
- Spalart - Allmaras Turbulence Model



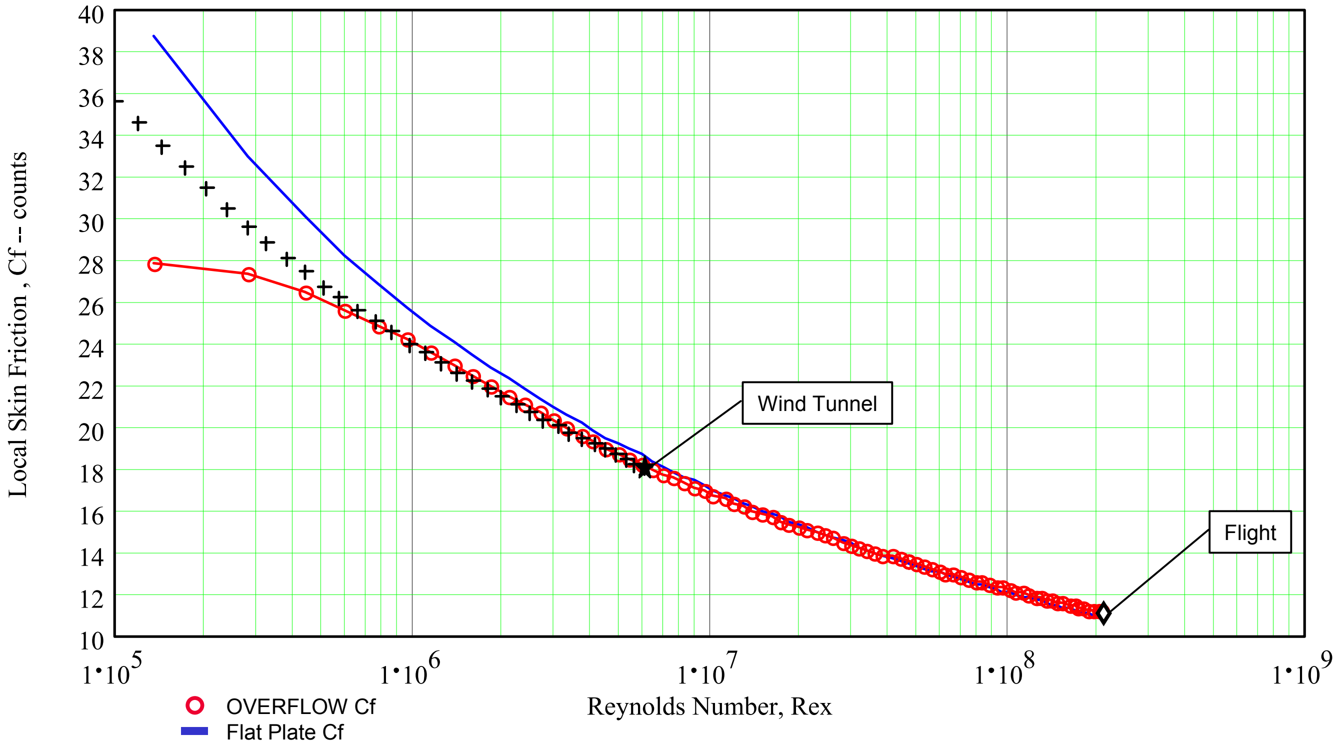


Nasa Ames OVERFLOW Local Cf Calculations Comparisons with Flat Plate Cf

Mach = 2.4

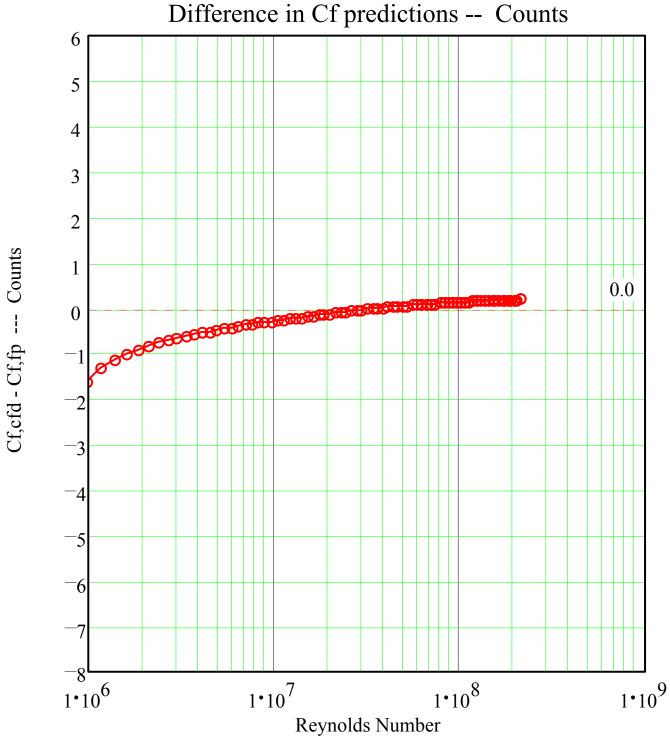
Menters SST Turbulence Model

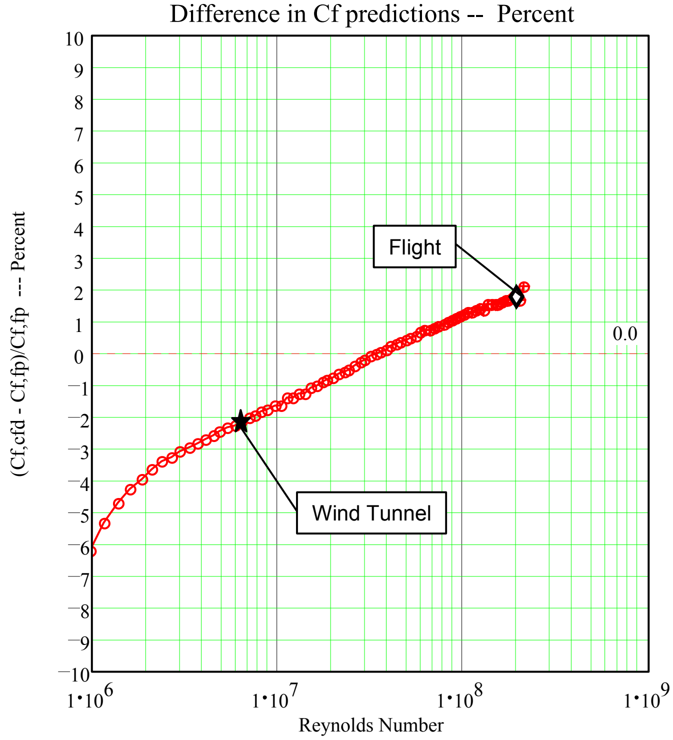
Unform vertical grid spacing



Differences Between CFD Calculated Local Cf and Flat Plate Cf

- Mach = 2.4
- NASA Ames OVERFLOW Code
- Menters SST Turbulence Model



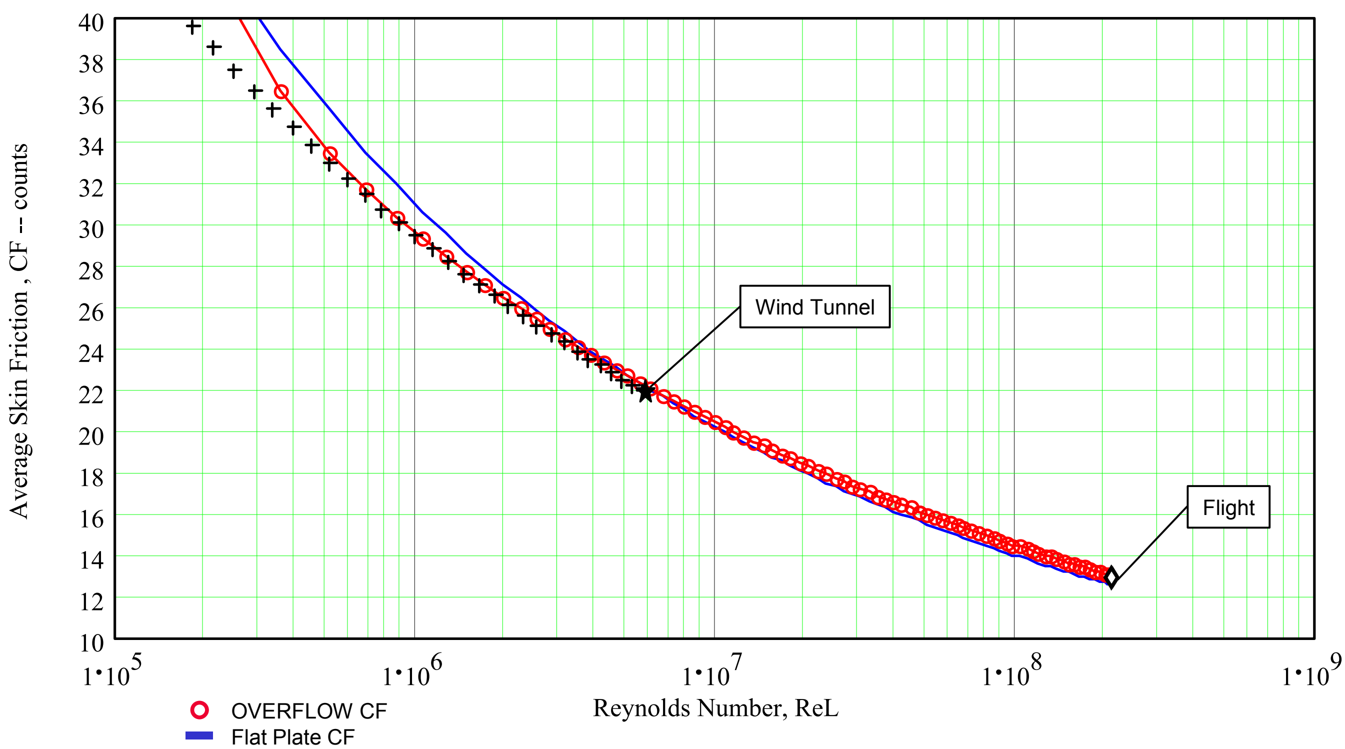


Nasa Ames OVERFLOW Average CF Calculations Comparisons with Flat Plate Cf

Mach = 2.4

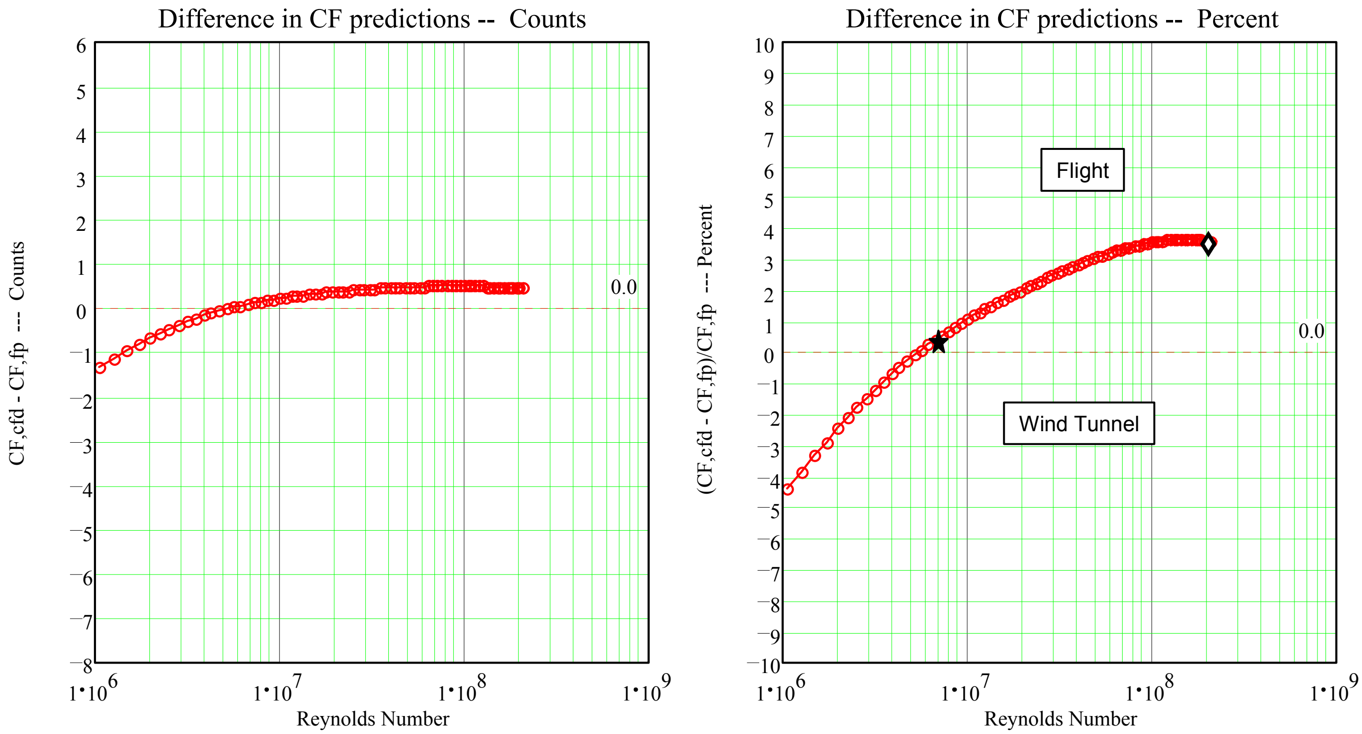
Menters SST Turbulence Model

Unform vertical grid spacing



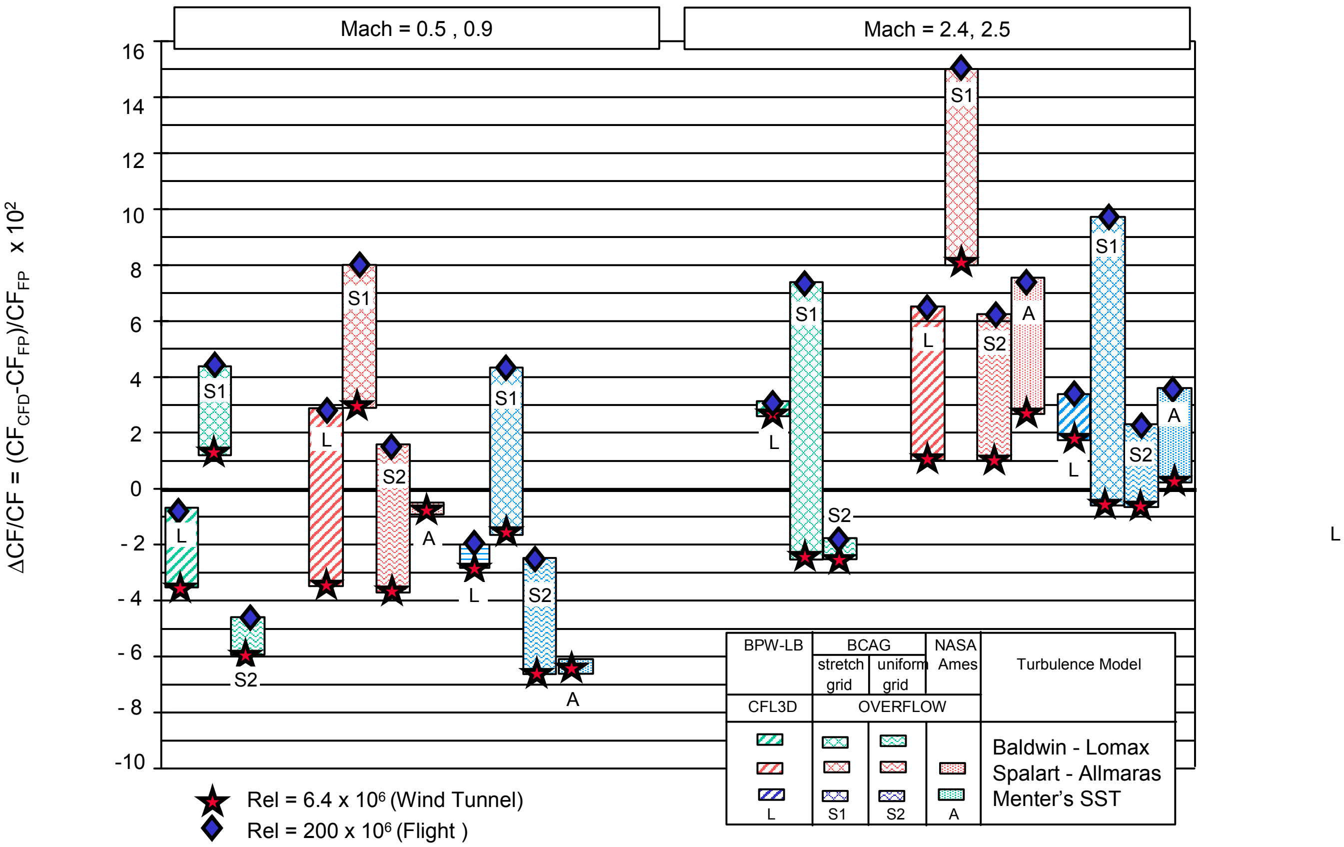
Differences Between CFD Calculated Average CF and Flat Plate CF

- Mach = 2.4
- NASA Ames OVERFLOW Code
- Menters SST Turbulence Model



CFD Flat Plate Viscous Drag vs Flat Plate Average Skin Friction Drag

Differences in percent



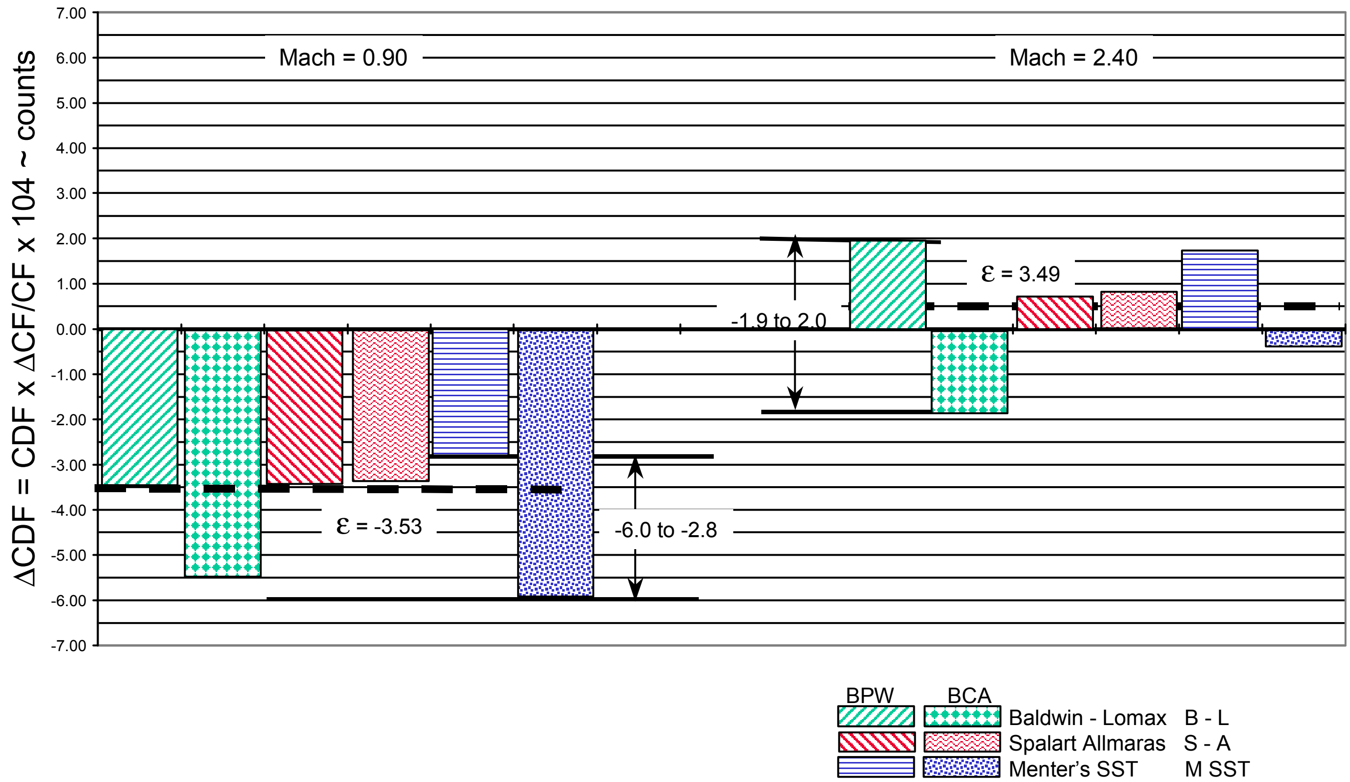
This is a comparative summary of all of the average skin friction prediction differences from the corresponding flat plate value. The comparisons shown are for Mach 0.5 or 0.9 and Mach 2.4 or 2.5. The four sets of calculations include:

- BPW-LB CFL3D results (L)
- BCAG OVERFLOW results with two different vertical grid schemes (S1 and S2)
- NASA Ames OVERFLOW results. (A)

Both wind tunnel and flight predictions are shown for the BPW-LB and the BCAG results.
The NASA Ames results include wind tunnel predictions for M = 0.9 and wind tunnel and flight predictions for Mach 2.4
It is apparent that the BCAG stretched grid results (S1) do not agree as well as the uniform grid calculations (S2).
The Spalart - Allmaras results are quite consistent for all three organizations (L, S2 and A).
The Spalart - Allmaras seem to provide the best agreement with the flat plate theory at Mach 0.9 even though the Reynolds Numbers trends differ. The Menters SST predictions seem to match the flat plate theory the best at Mach 2.4.
There are still, however, significant variations in the CFD drag predictions and the flat plate theory even for the simple flat plate geometry. Additional controlled wind tunnel test programs and corresponding CFD predictions will be necessary to resolve these differences.

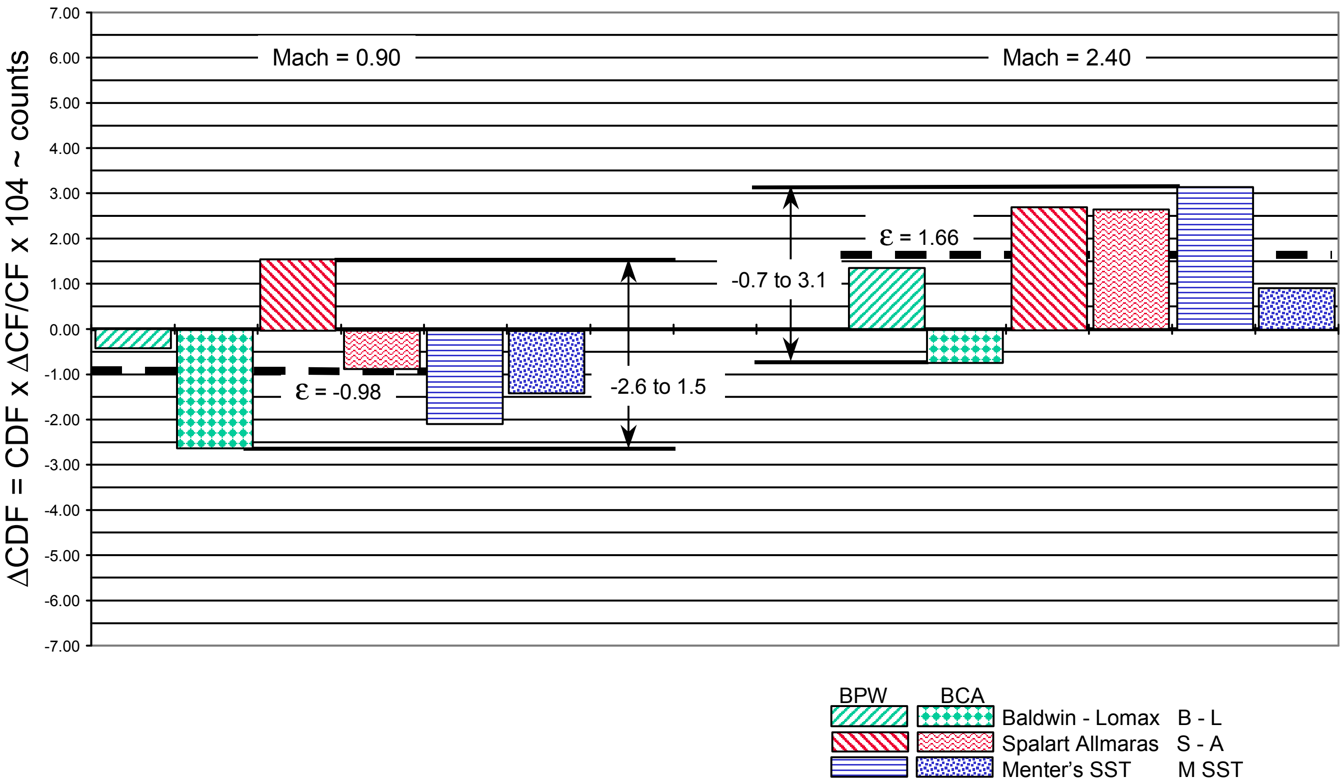
Skin Friction Drag Prediction Errors

- $\Delta CDF = CDF \times \Delta CF/CF$
- TC Complete Configuration
- Wind Tunnel Reynolds Number ~Rel = 6.2 x10^6



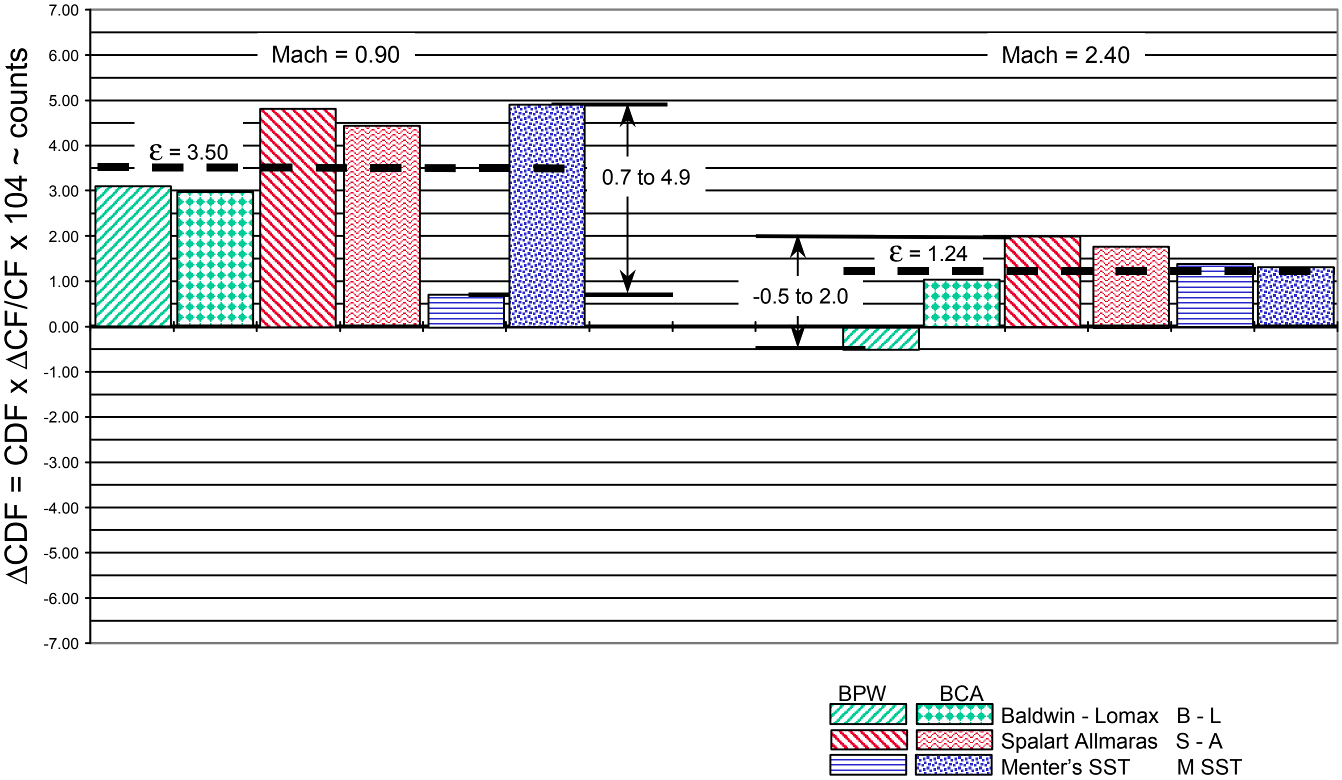
Skin Friction Drag Prediction Errors

- ΔCDF = CDF x ΔCF/CF
- TC Complete Configuration
- Full Scale Reynolds Number ~Rel = 180 x10[6]



Skin Friction Drag Prediction Errors - Wind Tunnel to Flight

- $\Delta CDF_{W\ to\ F} = \Delta CDF_{FS} - \Delta CDF_{WT}$
- TC Complete Configuration
- Reynolds Number Change ~Rel = 6.2×10^6 to 180×10^6



Conclusions

- Modified incompressible CF equations and improved T*/T method predict “mean” of available flat plate skin friction drag measurements
- BPW-LB CDL3D And BCA OVERFLOW CF predictions with the Spalart - Allmaras Turbulence Model are consistent and show a large difference in the variation of CF with Reynolds Number compared to the flat plate CF predictions
- The Spalart - Allmaras Cf predictions indicate a laminar to turbulent transition characteristic. This is the source of the large Reynolds Number variations
- The BPW-LB CFL3D CF predictions agree better with the flatp plate theory, and therfore also the test data, then the BAC OVERFLOW predictions
- Menter’s SST slightly underpredicts CF at low Mach Numbers, But overall best predicts flat plate fully turbulent flow CF
- BAC OVERFLOW results include:
  - CFD skin friction predictions vary with vertical grid spacing scheme.
  - “constant grid spacing” near the wall, CF predictions appear better than “stretched grid spacing” predictions
- Initial assessment of ARC OVERFLOW predictions show significant differences in the predictions using the Spalart- Almaras and the Menter SST Turbulence Models
- Additional effort is necessary to understand and resolve the CF prediction differences

The conclusions of this study are shown in the Figure.