AIAA JOURNAL
Vol. 31, No. 1, January 1993

# Three-Dimensional Hypersonic Shock Wave/Turbulent Boundary-Layer Interactions

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## Abstract

EXPERIMENTAL data for a series of three-dimensional shock wave/turbulent boundary-layer interaction flows at Mach 8.2 are presented. The test bodies, composed of sharp fins fastened to a flat plate test surface, were designed to generate flows with varying degrees of pressure gradient, boundary-layer separation, and turning angle. The data include surface pressure, heat transfer, and skin friction distributions as well as limited mean flowfield surveys in both the undisturbed and interaction regimes. The data were obtained for the purpose of validating computational models of these hypersonic interactions.

## Contents

Many experiments have been reported for three-dimensional swept shock interactions,[1] but acceptable hypersonic experimental data are almost nonexistent.[2] This work presents hypersonic swept shock data of sufficient resolution and quality to be used as a data base for validating turbulence models and computations as well as adding to the fundamental understanding of hypersonic interactions. The data obtained included surface pressure, skin friction, and heat transfer distributions along with detailed flowfield surveys. (Further details and data tabulations for this work can be found in Refs. 3–5.) We feel that turbulent flow models should be evaluated for relatively simple three-dimensional flows such as the present work before they are used for the more complex flows representative of an actual flight vehicle.

The experiments were conducted in the NASA Ames 3.5-ft hypersonic wind tunnel at Mach 8.2 at a freestream unit Reynolds number of $4.87 \times 10^6$/m. The test model consisted of a sharp flat plate that was 76 cm wide, 220 cm long, and 10 cm thick. Sharp fins were positioned on this test model approximately 176 cm downstream of the flat plate leading edge. Fin angles varied from 5 to 15 deg. The turbulent boundary-layer thickness approaching the fin leading edge was approximately 4 cm. The fin height of about six boundary-layer thicknesses produced a semi-infinite swept interaction over the entire span of the test region. Oil flow visualizations of the skin friction lines on both the flat plate and fin surfaces were obtained for the 10- and 15-deg fin cases. The laser interferometer skin friction (LISF) technique[3] was used to measure surface skin friction distribution in the interaction region for the 10- and 15-deg fin cases. Errors in the data reduction technique were found after publication of Ref. 3; a detailed explanation and the corrected skin friction data can be found in Ref. 5. This is the first time, to the authors' knowledge, that the LISF method has been successfully used in hypersonic flows.

The surface pressure, skin friction, and heat transfer distributions on the flat plate surface for fin angles of 10 and 15 deg are shown in Fig. 1. Pressure plateaus, indicative of flow separation, are evident. The heat transfer plateaus are much less pronounced than those of the pressure. The undisturbed flat plate boundary layer $c_f$ level is $1.00 \times 10^{-3}$, which agrees well with the values of $0.94 \times 10^{-3}$ and $0.98 \times 10^{-3}$ obtained by the floating-element balance and Clauser chart technique, respectively.[3] Between the inviscid shock location and the fin surface, there is an increase in skin friction and heat transfer to several times the undisturbed boundary-layer level. These are probably due to the lambda shock structure of the interaction, which causes the impingement of a high-speed jet on the flat plate in the vicinity of the attachment line.[1]

The Reynolds analogy for the fin angles are shown in Fig. 2 (using the corrected skin friction results given in Ref. 5). In the undisturbed flow (large z values), $2 \times C_H/c_f \approx 1.2$, which is reasonable. Surprisingly, the simple Reynolds analogy also holds for most of these flowfields. But we would like to emphasize that *both* the heat transfer and skin friction must be measured (and not assumed) before any conclusion can be reached concerning the validity of the Reynolds analogy for other complex flows. This is particularly important in devel-

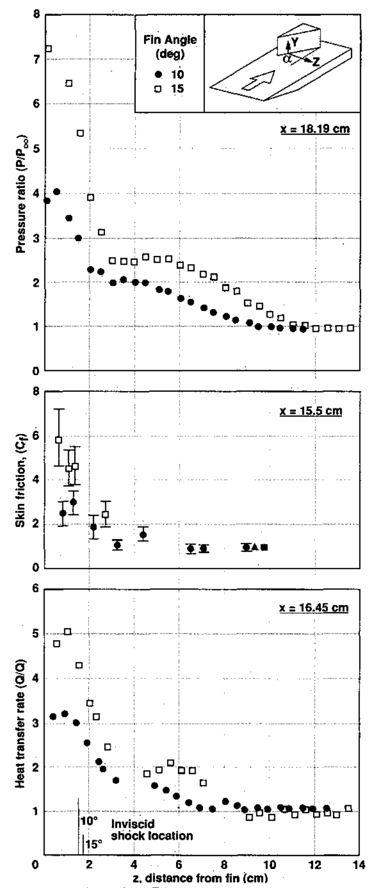


**Fig. 1 Flat plate surface pressure, heat transfer, and skin friction distributions for the 10- and 15-deg fin cases.**

Received June 12, 1991; synoptic received May 12, 1992; accepted for publication May 18, 1992. Full paper available at AIAA Library, 555 West 57th Street, New York, NY 10019. 

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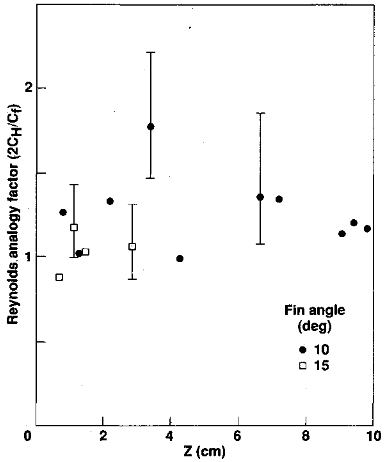


**Fig. 2 Flat plate Reynolds analogy factor for the 10- and 15-deg fin cases.**

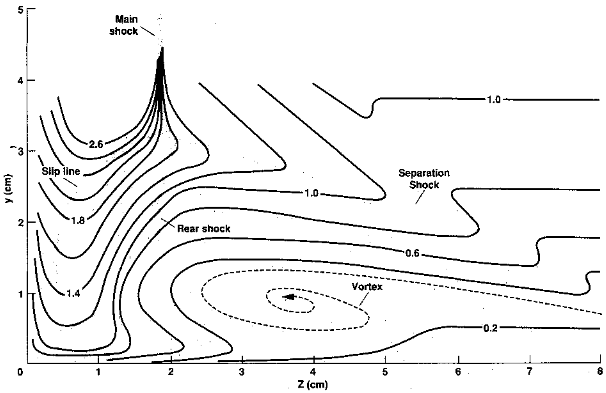


**Fig. 3 Flowfield pitot pressure contours, 15-deg fin, $x = 17.44$ cm.**

oping any data base against which competing turbulence flow models will be tested.

Boundary-layer surveys were made for the 10- and 15-deg fin cases, using a previously calibrated three hole ("cobra") pitot probe. These surveys were spaced sufficiently close together (in y and z) to allow accurate contour plots to be drawn. The result for the 15-deg fin case is shown in Fig. 3. Superimposed on the contours are shaded areas indicating the postulated location of the main and separation shocks, rear shock, and slip lines. The primary vortex is also shown. These postulated locations were not measured but follow the observations of Ref. 1.

Experimental data for a three-dimensional shock wave/turbulent boundary-layer interaction flow at Mach 8.2 have been presented. These data (the first to the authors' knowledge to be obtained at hypersonic speeds for a three-dimensional shock wave/turbulent boundary-layer interaction flow) have sufficient resolution and accuracy to fully document this complex three-dimensional flowfield. In addition, they are meant to be used as a data base with which to validate existing or future computational models for these hypersonic flows.

## Acknowledgment

The authors were supported by a grant from NASA to Eloret Institute (NCC2-452).

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