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Effect of Specific Heat Ratio on Two-Dimensional Transonic Aerodynamics

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Abstract

HEAVY gases can be used to increase simulation Reynolds number. For this reason, and to test transonic modeling, interferograms were taken of 10% nonlifting biconvex airfoils in gases with specific heat ratios γ of 1.10-1.67. The airfoils were mounted in Ludwieg/shock tube-driven solid-wall test sections and run at chord Reynolds number of 0.80×10^6 to 5.5×10^6 with nominal Mach numbers M of 0.70 to 0.80. No γ effect was detected at subcritical M, and the data were in agreement with inviscid theory. A 13% systematic decrease in peak negative pressure coefficient and forward shock movement were observed as γ increased in supercritical flow, contrary to the predictions of inviscid theory. A model incorporating a viscous displacement correction explained these results.

Contents

New simulation problems can arise from changing test gases.[1] For the present study, real gas effects are calculated to be unimportant compared with a change in the specific heat ratio γ. This parameter appears in the similarity rules obtained from the small-disturbance form of the inviscid equations of motion, but it persists to first order only in transonic flow. Recent experiments have shown that some correlation may be achieved at supercritical M through use of transonic similarity.[2] However, the boundary-layer development depends on local properties, which change with γ. Thus the displacement thickness, transition point, separation point, and shock/boundary-layer interaction may also exhibit γ dependence.

This investigation primarily used a Ludwieg-tube-driven staged nozzle with a 30×40 cm cross-section solid-wall test section.[3] Biconvex airfoils 10% thick, with chords c of 9.8 and 7.3 cm, were pin mounted in windows centered 35 cm upstream of the choke. The airfoils had cross-sectional area blockages of 2.5 and 1.8%, tunnel half height H to c ratios of 2.0 and 2.7, and aspect ratios of 3 and 4, respectively. They were tested in unheated A, N_2, or CO_2 ($\gamma=1.67$, 1.40, 1.31). In order to avoid condensation, a shock-tube-driven 7.5×10 cm solid-wall test section was used for the Freon − 12 and SF_6 $\gamma=1.10$ experiments. For these a 10% biconvex airfoil with $c=2.5$ cm was pin mounted in windows centered 30 cm upstream of the choke, giving H/c and aspect ratio identical to the 9.8 cm airfoil in the Ludwieg tube. A diaphragm was pressure-broken to initiate test section flow with total pressures $\leq$ 1.4 atm in the Ludwieg tube and $\leq$ 4 atm in the shock tube. Shadowgraph framing-camera photos showed 10-30 ms of steady airfoil flow in the former case and 8 ms in the latter.

Test section M was determined with piezoelectric pitot and static tubes, with the uncertainty held to ±1% by averaging a number of runs. Airfoil data were obtained with a double-exposure holographic interferometer which used a passive Q-switched ruby laser ($\lambda=694$ nm) triggered by a delayed signal from an accelerometer. This instrument gave the test-section rms density (ρ) fluctuation integrated across the flow as $\leq$0.2% (i.e., see upstream flow on Fig. 1). Interferograms taken perpendicular to the airfoil helped to show that 3-D

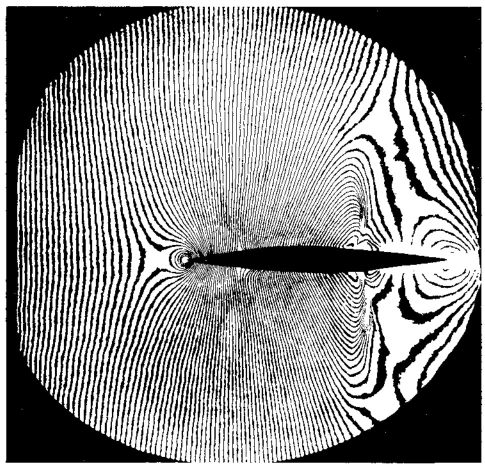

Fig. 1 Representative interferogram ($M=0.80$ in CO_2; $Re_c=2.7\times10^6$; $\Delta\rho/\rho_\infty=0.7$%/fringe; $\rho_\infty=0.37$ amagat).

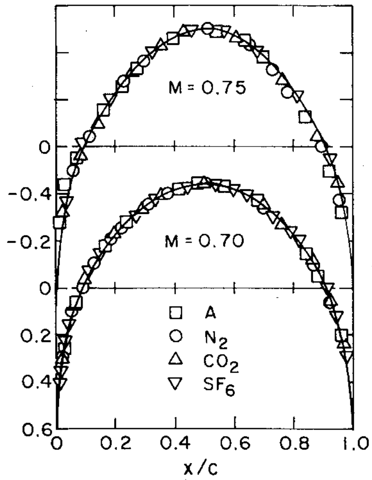

Fig. 2 Experimental results at supercritical M (SF_6 data from shock tube; solid lines are inviscid theory for $\gamma=1.4$, $H/c=2$).

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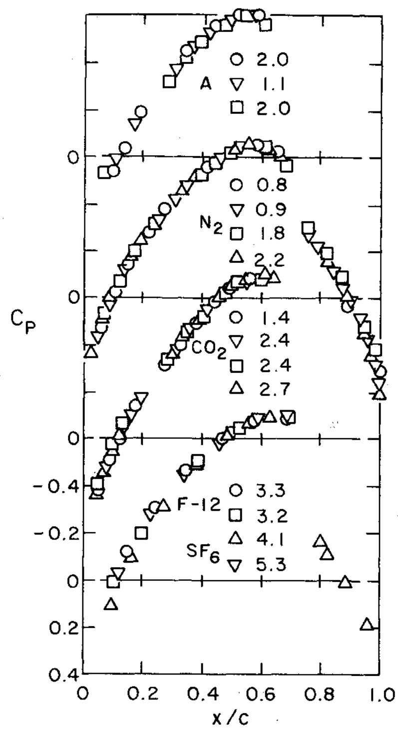

Fig. 3 Experimental results for $M = 0.80$ (numbers refer to Re_c 10^{-6}; F-12, SF_6 data from shock tube).

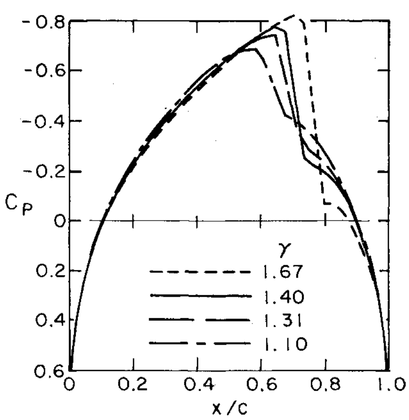

Fig. 4 Inviscid calculations ($M = 0.80$; $H/c = 2$).

effects were not important.[4] Fringe pattern symmetry was used to set angle of attack to ±0.05 deg of the non-lifting condition.

A representative interferogram of the flow about an airfoil is shown on Fig. 1. Fringe bending to the right corresponds to ρ increases from the freestream value (ρ_∞). ρ is high at the stagnation point, falls to a low value past midchord, and recovers again near the trailing edge. Shocks of limited vertical extent are visible where the enclosed fringes pile up to indicate rapid ρ change, and separation and a wake structure are often seen. Fringe locations next to the airfoil were measured with respect to the fringes ~1 c above. The <2% difference between the latter and the freestream was calculated,[5] and the ρ information then used to obtain the local pressure coefficient C_p from the isentropic relation. While a trip wire did ensure turbulent shock/boundary-layer interactions, no changes in C_p upstream of the shock were discernible. Interferogram sensitivity was calculated to range from 0.2 to 2% $\Delta\rho$ per fringe shift, with an accuracy of $\pm\sqrt{5}$%. C_p precision was then estimated to be ±3%. Adding in a C_p level uncertainty $\leq \pm 0.01$ due to a fringe reading accuracy of ±0.2 to ±0.5 yields an accuracy within ±4% at peak C_p.

Typical experimental C_p distributions are shown in Fig. 2, where a displaced ordinate separates $M = 0.70$ and $M = 0.75$ data. The symbol size encompasses the extremes of the data from at least three runs and agrees with the accuracy predictions. There are no shocks in these flows and c, Reynolds number Re, and γ effects were not discernible. Inviscid small disturbance theory[5] for $\gamma = 1.4$ flow with blockage is seen to be in excellent agreement, little γ effect being predicted.

Figure 3 shows C_p results for individual runs at $M = 0.80$, with a displaced ordinate for each gas. Again, no systematic c or Re dependence was observed, but the data do show a γ dependence. The overall experimental difference at minimum C_p between the SF_6 and A data is 13%, that between CO_2 and A is 10%. Note that the shock location appears to be only weakly affected by γ. Although little error is introduced by using the isentropic relation in the external flow downstream of the shock, strong separation could invalidate assignment of this C_p to the surface.

The numerical small-disturbance calculations[5] used transonic similarity variables modified so that C_p at the sonic point exactly matched the isentropic critical value. γ effects became significant at $M = 0.80$ where, as seen on Fig. 4, a γ increase moves the shock back and strengthens it. These predictions are in direct opposition to Fig. 3. Comparison of full potential[6] and small disturbance calculations for $H/c = \infty$ showed that this approximation was not the reason for the difference, and attention was directed to viscous modeling.

A displacement correction obtained from integral turbulent boundary-layer theory diverged the C_p calculation due to the large perturbations from layer thickness changes near the shock. This was avoided by approximating the calculated layer and its displacement beyond separation and into the wake with smoothing assumptions.[4] The resulting correction was particularly noticeable for the severely separated $\gamma = 1.67$ case, for which the peak negative C_p was lowered 25% and the shock moved 0.20 c forward. All of the corrected predictions were found to agree with Figs. 2 and 3 to within experimental accuracy, there being a persistent <4% over-prediction of the peak negative C_p at $M = 0.80$. The calculations showed that separation can be sensitive to γ through changes in the inviscid flow shock strength, and that the viscous layer before and after separation can move the shock and change C_p. Viscous effects may increase in importance at angle of attack, and further correlation will pace precision heavy gas testing with unmatched γ in supercritical flow.

Acknowledgment

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