Numerical Study on Using Sulfur Hexafluoride as a Wind Tunnel Test Gas

W. Kyle Anderson*
NASA Langley Research Center, Hampton, Virginia 23665

Abstract

A NUMERICAL study is presented that investigates effects of using sulfur hexafluoride, SF_6, as a substitute for air. Inviscid results for airfoils indicate that for transonic cases the shock location calculated for SF_6 is vastly different from that in air and moves progressively forward on the airfoil as the freestream pressure is increased and real gas effects become more pronounced. Application of a simple Mach number scaling procedure results in good correlation between SF_6 and air even for pressures at which nonideal gas effects are significant. Computations for subsonic turbulent flows over a NACA 0012 airfoil show that the maximum angle of attack at which steady lift can be obtained is different between air and SF_6. In addition, for SF_6, this angle of attack depends on the freestream conditions. Improved agreement with air can be achieved by altering the freestream Mach number according to the inviscid scaling procedure. Transonic results show that even with Mach number scaling, the shock location and skin friction values calculated between air and SF_6 are in disagreement. This is attributed to the limitations of the scaling procedure and to a thinner boundary layer for SF_6.

Contents

In an effort to improve on the capability of obtaining full-scale Reynolds numbers for wind tunnel testing of three-dimensional configurations, alternative test gases are currently being considered. One such gas is sulfur hexafluoride, SF_6, which is odorless, colorless, nonflammable, nontoxic, and essentially inert.[1] Its high molecular weight makes this gas attractive as an air substitute in order to achieve high Reynolds numbers. Particular interest lies in the use of pressurized wind tunnels because further increases in Reynolds numbers can be achieved and because Reynolds number and Mach number effects may be studied independently. Unfortunately, even at low pressures, sulfur hexafluoride does not have the same thermodynamic properties as air. Furthermore, unlike air, SF_6 is a nonideal gas whose intemal energy, speed of sound, and other thermodynamic properties are dependent on both pressure and temperature. While this poses no problem for incompressible flows, compressibility effects such as shock locations and boundary-layer properties are not the same between the two gases, making correlations with air difficult.

For studying the aerodynamic effects caused by the use of SF_6, numerical solutions to the two-dimensional Euler and Navier-Stokes equations are obtained for airfoils at various flow conditions. For viscous calculations, the thin-layer approximation to the Navier-Stokes equations is used in the present analysis. The equations are solved with an implicit, finite-volume, upwind-differenced algorithm in which the spatial derivatives of the fluxes are split into forward and backward contributions using flux-vector splitting so that type-dependent differencing can be used. The flux-vector splitting method used is that of Van Leer,[2] with the modifications to the flux formulas necessary for real gas calculations given in Ref. 3. For all turbulent calculations, the Baldwin-Lomax turbulence model is employed[4] where it should be noted that, for both air and SF_6, the turbulent Prandtl number is assumed to be constant with a value of 0.8.

For the present calculations, pure SF_6 is assumed. The thermodynamic quantities are determined using the equation of state given in Ref. 1. Deviations of quantities such as internal energy and speed of sound from the ideal gas state are accounted for using departure functions.[5] Further detail can be found in Ref. 6. For SF_6, the viscosity is determined with a simple linear fit,[7] and the thermal conductivity is given by a power law.[7]

For calculations in air, the gas is assumed to be both thermally and calorically perfect. The molecular viscosity is computed with Sutherland's law, and the thermal conductivity is computed on the basis of a constant Prandtl number.

Inviscid calculations have been obtained for a NACA 0012 airfoil for both subsonic and transonic flow conditions, although only those for transonic conditions are shown here. Results obtained using SF_6 at several freestream pressures are compared with results for air. Note that calculations for air are not shown as a function of pressure since air is assumed to obey ideal gas laws and is thus independent of the freestream pressure.

Transonic results for a NACA 0012 airfoil at a freestream Mach number of 0.8 and an angle of attack of 1.25 deg are shown in Fig. 1. The solution for these conditions in air has been calculated many times in the past and is characterized by a weak lower surface shock and a moderate strength shock on the upper surface. As expected, the SF_6 pressure distributions do not agree with that of air. The upper surface shock for SF_6 moves increasingly forward as the freestream pressure is increased from 1 to 10 atm, and the lower surface shock completely vanishes.

An attempt has been made to determine a systematic Mach number scaling procedure appropriate for use with SF_6 so that improved correlations between air and SF_6 can be obtained. This is done by exploiting results from small disturbance theory through the use of the similarity parameter that is valid for subsonic, transonic, and supersonic flows with small disturbances[8]:

$$\kappa = \frac{1 - M_\infty^2}{\left[\tau M_\infty(\gamma' + 1)\right]^{2/3}} \tag{1}$$

where M_∞ is the freestream Mach number, τ represents a thickness parameter, and γ' is a parameter that is equal to the ratio

Presented as Paper 90-1421 at the AIAA 16th Aerodynamics Ground Testing Conference, Seattle, WA, June 18–20, 1990; received July 24, 1990; synoptic received Dec. 3, 1990; accepted for publication Jan. 9, 1991. Full paper available from AIAA Library, 555 W. 57th St., New York, NY 10019. Copyright © 1990 by the American Institute of Aeronautics and Astronautics, Inc. No copyright is asserted in the United States under Title 17, U.S. Code. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Governmental purposes. All other rights are reserved by the copyright owner.

*Research Scientist. Computational Aerodynamics Branch, Mail Stop 128.

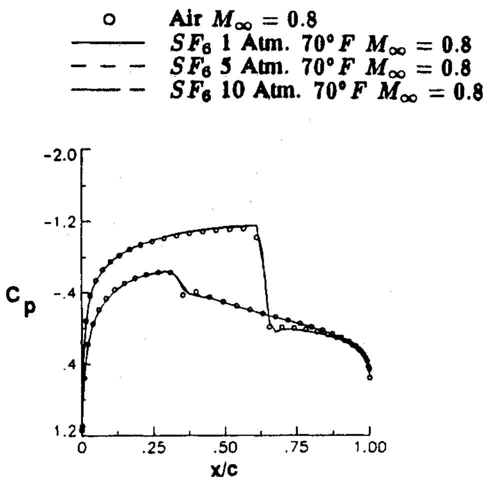

Fig. 1 Comparison of pressure coefficients for air and SF_6 at 70°F and 1, 5, and 10 atm for NACA 0012; $M_\infty = 0.80$; $\alpha = 1.25$ deg.

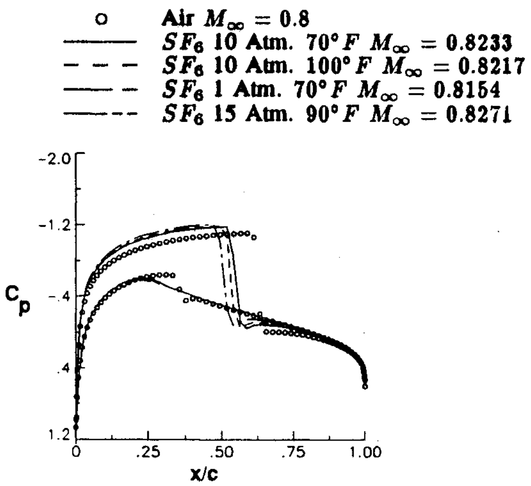

Fig. 2 Effect of transonic similarity scaling for SF_6 using $\gamma' = (1 + \partial a^2/\partial h)_s$ for NACA 0012; $M_\infty = 0.8$ (air); $\alpha = 1.25$ deg.

of specific heats for perfect gases. By using an appropriate definition of γ', a new freestream Mach number can be obtained for use in the SF_6 calculations by matching the similarity parameter obtained for air. Afterward, the calculated lift and pressure coefficients can be corrected according to small disturbance theory. It is shown in Ref. 6 that the appropriate definition of γ' useful for scaling is given by

$$\gamma' = 2\Gamma_\infty - 1 = \left(1 + \frac{\partial a^2}{\partial h}\right)_{s,\infty} \tag{2}$$

where a, h, and s represent the speed of sound, enthalpy, and entropy, respectively. The parameter Γ is referred to as the fundamental derivative[9] and is given by

$$\Gamma = -\frac{v}{2}\frac{\left[\left(\dfrac{\partial^2 p}{\partial v^2}\right)_s\right]}{\left[\left(\dfrac{\partial p}{\partial v}\right)_T\right]} \tag{3}$$

where v is the specific volume and T is the temperature. The latter form of γ' given in Eq. (2) is of particular interest since its use in linearizing the speed of sound in deriving the small disturbance potential flow equations leads to equations that are identical to those of an ideal gas but with γ' used in place of γ.[10]

Results obtained through the scaling procedure are shown in Fig. 2 for several combinations of freestream pressure and temperature. It is seen that very consistent results are obtained in that the shock locations are invarient and agree reasonably well with that of air for all temperature and pressure combinations.

Note that the scaling procedure is easily reversed; given conditions in the freestream for SF_6, the equivalent Mach number for air is easily obtained. Also note that this scaling procedure is valid only for two-dimensional calculations; however, three-dimensional scaling laws exist but require modifications to the aspect ratio as well as to the Mach number.

Although not shown, computations for subsonic turbulent flows over a NACA 0012 airfoil show that the maximum angle of attack at which steady lift can be obtained is different between air and SF_6. In addition, for SF_6, this angle of attack is dependent on the freestream conditions. Improved agreement with air can be achieved by altering the freestream Mach number according to the inviscid scaling procedure. Transonic results show that even with Mach number scaling, the shock location and skin friction values calculated between air and SF_6 are in disagreement. This is attributed to the limitations of the scaling procedure and to the thinner boundary layer for SF_6.

References

[1] Allied Chemical Corporation, TB524-99-1/87-2.

[2] Van Leer, B., "Flux Vector Splitting for Euler Equations," *Eighth International Conference on Numerical Methods in Fluid Dynamics,* edited by E. Krause, Vol. 170, Lecture Notes in Physics, 1982, pp. 507–512.

[3] Grossman, B., and Walters, R. W., "An Analysis of Flux-Split Algorithms for Euler's Equations with Real Gases," AIAA Paper 87-1117, June 1987.

[4] Baldwin, B. S., and Lomax, H., "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows," AIAA Paper 78-257, Jan. 1978.

[5] Modell, M., and Reid, R. C., *Thermodynamics and Its Applications,* Prentice-Hall, Englewood Cliffs, NJ, 1983.

[6] Anderson, W. K., "Numerical Study on the Use of Sulfur Hexafluoride as a Test Gas for Wind Tunnels," AIAA Paper 90-1421, June 1990.

[7] Technical Service Bulletin on Sulfur Hexaflouride, General Chemical.

[8] Liepmann, H. W., and Roshko, A., *Elements of Gas Dynamics,* Wiley, New York, 1957.

[9] Thompson, P. A., and Lambrakis, K. C., "Negative Shock Waves," *Journal of Fluid Mechanics,* Vol. 60, Aug. 1973, pp. 187–208.

[10] Wagner, B., and Schmidt, W., "Theoretical Investigations of Real Gas Effects in Cryogenic Wind Tunnels," *AIAA Journal,* Vol. 16, No. 6, 1976, pp. 580–586.