High-Enthalpy Nonequilibrium Carbon Dioxide Nozzle and Wedge Flows: Experiment and Calculations

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Theme

AN experimental survey is presented of carbon dioxide nozzle expansions from a reservoir at high specific enthalpy, h_o. The aim is to test the chemical model assumed for the gas in numerical calculations[1] and to determine the conditions at the nozzle exit as a function of reservoir condition. Static pressure, which is sensitive to nonequilibrium effects, and pitot pressure are in good agreement with Ref. 1. The gas model is also tested in flows over bodies by comparing optical interferograms of wedge flows with numerical calculations, and it is found that vibrational relaxation, which is unimportant in nozzle flow, plays a significant part here. The results confirm the reliability of the free piston shock tunnel for the study of high-enthalpy flows of carbon dioxide.

Contents

Apart from the temperature, the flow variable which is most sensitive to nonequilibrium effects in nozzle expansions of carbon dioxide is the static pressure.[1] At the same time, the pitot pressure is virtually independent of nonequilibrium effects. Fitting a measured pitot traverse of the nozzle flow to a numerical calculation therefore determines the effective area ratio, A/A^*, where A^* is the throat area of the nozzle, thus eliminating the uncertainty about the displacement thickness of the boundary layer at the nozzle wall. An example of such a fit is shown for a conical nozzle with 7.5° semiangle in Fig. 1, which demonstrates that the slopes of the calculated and measured pitot pressure curves agree over a large range of area ratio. The fit indicates a positive displacement thickness which is confirmed by transverse pitot pressure traverses in the vicinity of the wall. Also, sting-mounted axisymmetric probes do not insulate the transducer sufficiently well from mechanical vibrations. However, by using a flat plate, bolted rigidly to the nonrecoiling part of the test section it is possible to make the probe so stiff that the lower frequency vibrations in the measuring range are virtually eliminated. The static pressure signal, recorded by a Kistler-type 603H device, is filtered to remove high-frequency mechanical noise and corrected for acceleration and leading-edge viscous interaction. Acceleration amounts to about 10% of the total signal and is measured by firing a shot with the pressure hole closed. The effect of leading-edge interaction (about 7% of signal) is inferred from schlieren photographs. Accurate alignment of the plate with the nozzle axis ensures that the error arising from misalignment is only about ± 3%. The overall accuracy of the static pressure determination is estimated as ± 12%.

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Index categories: Reactive Flows; Nozzle and Channel Flow.

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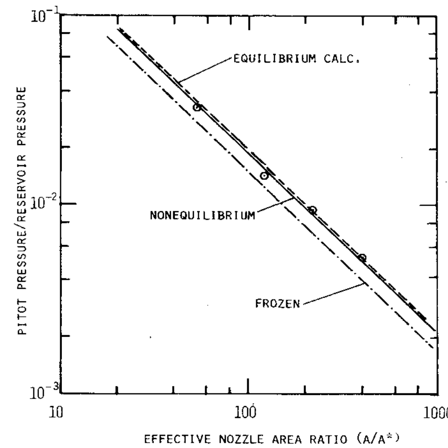

Fig. 1 Normalized pitot pressure, $T_o = 10250$ K, $P_o = 238$ atm.

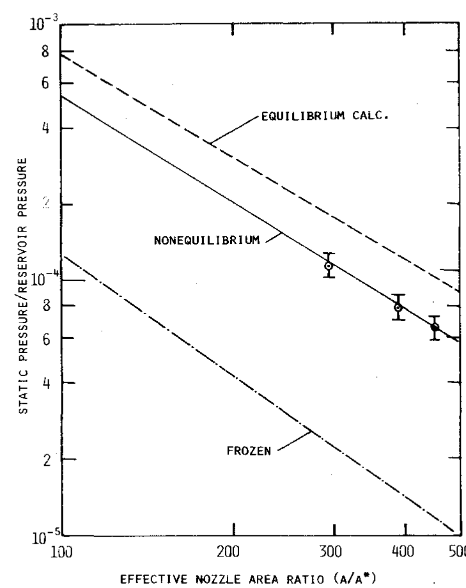

Fig. 2 Normalized static pressure, $T_o = 10250$ K, $P_o = 238$ atm.

An example of the static pressure distribution is shown in Fig. 2. As in Fig. 1, the experimental results are compared with calculated equilibrium, frozen, and nonequilibrium flow. It is evident that the agreement between calculated and measured values is good, indicating that the chemical model used in Ref. 1 is satisfactory. It should be noted that the slope of the pressure-area curve in logarithmic coordinates is equal to minus the ratio of specific heats at large area ratio, and that the agreement between calculation and experiment therefore gives an approximate confirmation of the gas composition. To show the dependence of static pressure on reservoir condition, the measured and calculated pressure at an area ratio of 295 are plotted against reservoir temperature, T_o (constant

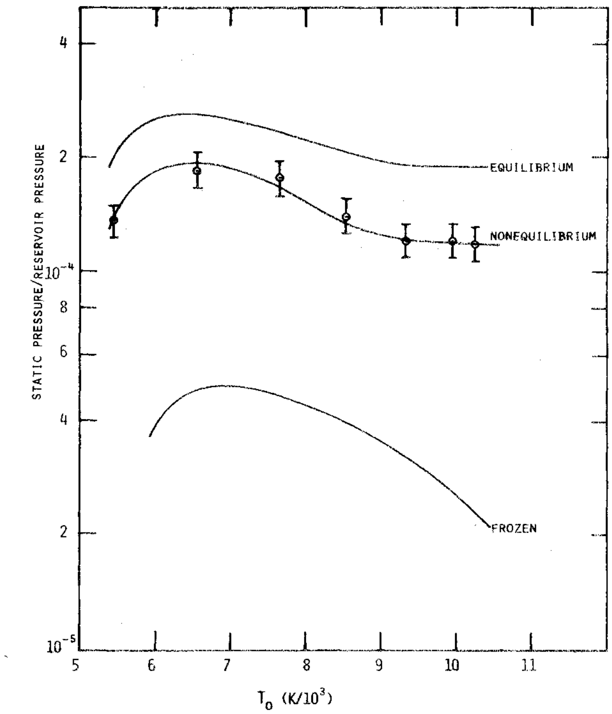

Fig. 3 Normalized static pressure as a function of reservoir temperature, $P_o = 238$ atm, $A/A^* = 295$.

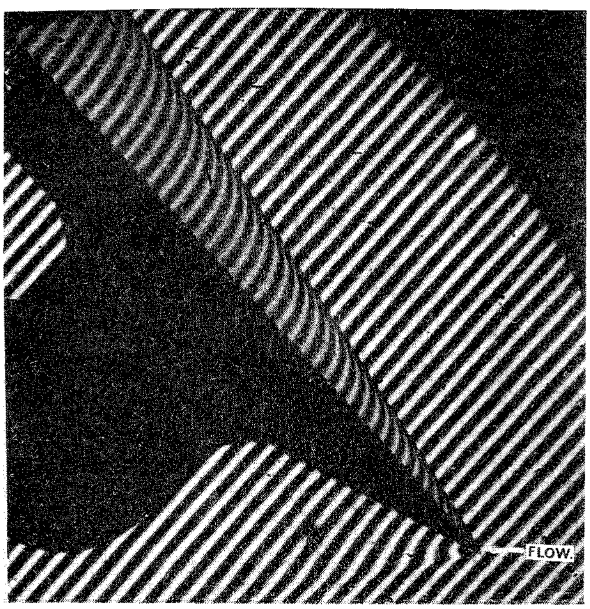

Fig. 4 Interferogram of wedge flow at lower enthalpy. $T_o = 6360$ K, $P_o = 201$ atm, incidence = 43°.

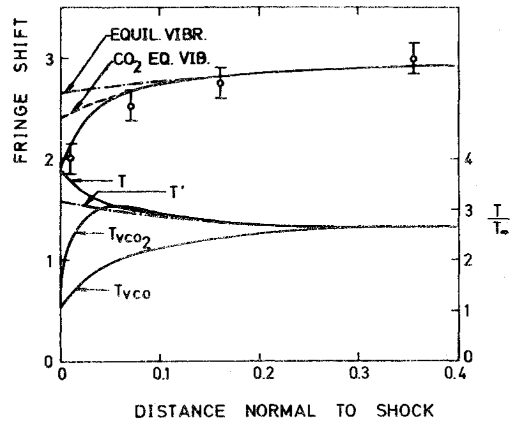

Fig. 5 Fringe shift and temperature profiles in the flow of Fig. 4.

reservoir pressure, P_o) in Fig. 3. The good agreement with the calculated curve gives an indirect confirmation that the temperature dependence of the chemical rates assumed in Ref. 1 is satisfactory.

To complete an approximate experimental determination of the test section conditions, the freestream density is determined from wedge-flow interferograms taken at conditions where the wedge shock is straight (near equilibrium or near frozen, see Ref. 2). The error in freestream density, ρ_∞, obtained in this manner is ± 15%. Using this with the measured pitot pressure, and assuming the latter to be approximately equal to $\rho_\infty u_\infty^2$, the freestream speed, u_∞, can be estimated to an accuracy of about ± 10%. Results obtained in this manner agree with calculations.

To test the rate model of the gas on the dissociating path as well, reacting wedge flows are studied, using optical interferometry, and compared with numerical calculations. The latter used a method[2] which integrates the governing differential equations starting from the known shock shape (obtained from the interferogram). Figure 4 gives an example of an interferogram at one of the lower values of h_o to illustrate the importance of vibrational relaxation at these conditions. This is brought out by a comparison of the measured fringe shift with the results of the calculation (Fig. 5). Results of the calculation based on vibrational equilibrium are seen to be significantly different in the vicinity of the shock, from those with vibrational relaxation. Also shown in Fig. 5 are the translational temperature with (T) and without (T') vibrational relaxation, as well as the vibrational temperatures of CO_2 and CO, respectively (T_{VCO_2}, T_{VCO}), as calculated.

References

[1]Ebrahim, N.A. and Hornung, H.G. "Nonequilibrium Nozzle Expansions of Carbon Dioxide from a High-Enthalpy Reservoir," *AIAA Journal*, Vol. 11, Oct. 1973, pp. 1369-1372.

[2]Kewley, D.J. and Hornung, H.G., "Non-equilibrium Dissociating Nitrogen Flow over a Wedge," *Journal of Fluid Mechanics*, Vol. 64, March 1974, pp. 725-736.