SYNOPTIC: Some Characteristics of Exhaust Plume Rarefaction, E. P. Muntz, B. B. Hamel, and B. L. Maguire, General Electric Company, Valley Forge, Pa.; *AIAA Journal*, Vol. 8, No. 9, pp. 1652–1658.

Jets; Rarefield Flows

Theme

Discusses rarefaction phenomena in highly underexpanded exhaust plumes.

Content

Analyzes exhaust plume rarefaction from continuum flow to scattering regime. A rarefaction parameter is found that will correlate certain of the rarefaction phenomena from shock broadening to the penetration of background gas into the core of the plume. The parameter is

$$\xi = D(P_S P_{B\infty})^{1/2}/T$$

where D = sonic orifice diameter, cm; P_s = stagnation chamber pressure, dynes/cm²; $P_{B\infty}$ = background pressure, dynes/cm²; and T = temperature, °K.

Experimental results for molecular beam facilities are shown to be consistent with the scaling. Experimental measurement of the plume shock broadening are shown to be correlated by ξ.

Background gas is predicted to penetrate to a distance r_P from the exit orifice of the underexpanded flow:

$$r_p = \epsilon \bar{V}_\infty \pi \sigma_{Bj}{}^2 n^* r^{*2}/\bar{C}_B{}^1$$

where $\bar{V}_\infty$ = relative velocity, σ_{Bj} = background-jet collision diameter, n^* = sonic number density, r^* = sonic radius, and $\bar{C}_B{}^1 = f(\bar{C}_B)$, background mean molecular speed.

Some Characteristics of Exhaust Plume Rarefaction

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In this paper the rarefaction of a free jet expanding into a region of finite background pressure is considered. It is found that the rarefaction process can be described by a simple rarefaction parameter $D(P_s P_{B_\infty})^{1/2}/T$. Here D is the sonic orifice diameter, P_s is the reservoir pressure, P_{B_∞} is the background pressure and T is the background and reservoir temperatures which are considered to be the same. A simple scattering formulation of the complex physical problem is proposed. Comparison of the scattering prediction and previous molecular beam flux measurements by Fenn and Anderson are presented. A consistent physical description of a plume's approach to the limit of expansion into a perfect vacuum is discussed.

Nomenclature

$\bar{C}$ = mean molecular speed
D = sonic orifice diameter, cm
k = Boltzmann's constant
n = number density, molecules/cc
P = pressure, dynes/cm²
$\mathcal{R}$ = density ratio across shock
r = distance along jet streamline
T = temperature, °K
V = velocity
$\bar{V}$ = relative velocity; $\bar{V}_\infty = V_\infty + \bar{C}_B{}^1$
X_M = distance from sonic orifice to the Riemann wave
δ = shock thickness
γ = ratio of specific heats
λ = mean free path
μ = viscosity
ν = collision frequency
σ = collision diameter
ξ = rarefaction parameter, $\xi = D(P_s P_{B\infty})^{1/2}/T$

Superscripts

$*$ = reference or sonic condition

Subscripts

B = background molecule
jI = ideal jet condition
j = jet molecule
s = stagnation region condition
∞ = freestream

Presented as Paper 69-657 at the AIAA Fluid and Plasma Dynamics Conference, San Francisco, Calif., June 16–18, 1969; submitted March 10, 1969; revision received March 9, 1970. The authors would like to thank A. L. Cooper for useful discussions during the course of this investigation. E. Strybuc was a significant contributor to the experimental work. Support for the work was received from the Air Force Office of Scientific Research, Mechanics Division; the Office of Naval Research, Project Squid; and the General Electric Company.

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I. Introduction

THE continuum to rarefied transitional behavior of exhaust plumes is considered. Phenomena that are discussed are associated with the transition from a low altitude