in which ρ_s is the density of the solid particles.

To obtain the quantity $(1/u_s)(du_s/dx)$, we can measure the curvature of the particle streamline $S(x)$ since

$$\frac{1}{u_s}\frac{du_s}{dx} = -\frac{S''(x)}{S'(x)}$$

Another way to obtain $(1/u_s)(du_s/dx)$ is by measuring the particle number density behind the shock n_s. If the number density is measured along a horizontal line x', then

$$\frac{1}{u_s}\frac{du_s}{dx} = -\frac{1}{n_s \sin\theta}\frac{\partial n_s}{\partial x'}$$

where θ is the shock angle. u_s/u is known exactly at the shock. By varying the wedge angle, the drag coefficients can be obtained over a range of relative Reynolds numbers.

References

[1] Hoglund, R. F., "Recent advances in gas-particle nozzle flows," ARS J. **32**, 662–671 (1962).

[2] Carrier, G. F., "Shock waves in a dusty gas," J. Fluid Mech. **4**, 376 (1958).

[3] Rudinger, G., "Some properties of shock relations in gas flows carrying small particles," Cornell Aeronautical Lab., Project SQUID, TR CAL-87-P (1963).

[4] Kliegel, J. R., "Gas particle nozzle flow," *Ninth Symposium (International) on Combustion* (Academic Press, New York, 1963), p. 811.

[5] Rudinger, G., "Experiments on shock relations in particle suspensions in a gas and preliminary determination of particle drag coefficients," Cornell Aeronautical Lab., Project SQUID, TR CAL-90-P (1963).

[6] Ingebo, R. D., "Drag coefficients for droplets and solid spheres in clouds accelerating in airstream," NACA TN 3762 (1956).

[7] Morgenthaler, J. H., "Analysis of two-phase flow in supersonic exhausts," *Detonation and Two-Phase Flow* (Academic Press, New York, 1962), p. 145.

Velocity Profile in the Half-Jet Mixing Region of Turbulent Jets

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A WIDELY used similarity parameter for the nondimensional velocity U/U_0 of jets with exit velocity U_0 is the quantity $\sigma(Y - Y_{0.5})/x$. The x-axis is chosen parallel to the freestream direction or along the axis of an axisymmetric jet. $(Y - Y_{0.5})$ is the lateral distance between point of measurement and the point at which the velocity is half that of the exit velocity, and σ is a constant determined by fitting the measured velocity profile to the theoretical one of either Tollmein or Gortler. The quantity σ is not a universal constant and its value depends on the characteristics of an individual jet. The effect of Mach number on σ has been summed up in Fig. 12 of Ref. 1. See also Refs. 2 and 3. Because of the fairly wide scattering of data, it is hard to give a definite relationship between the two.

However, the variation of σ with different jet parameters (e.g., exit Reynolds number, Mach number, temperature, turbulence level) will be taken care of automatically if one uses the alternate parameter $(Y - Y_{0.5})/(Y_{0.9} - Y_{0.1})$ where $(Y_{0.9} - Y_{0.1})$ is the distance between the points at which the velocity is, respectively, 0.9 and 0.1 of the exit velocity ($U/U_0 = 0.9$ and $U/U_0 = 0.1$). Abramovich[4] used this parameter for the dimensionless velocity profile of his round jet and obtained a profile which fits well with that obtained from results of the plane jet of Albertson et al.[5] Results from our own hot-wire measurements in a 4-in. low-speed round jet also agree well with Abramovich's profile. In view of this good agreement, a few experimental data of other investigators were compiled and replotted for comparison in Table 1 and Fig. 1.

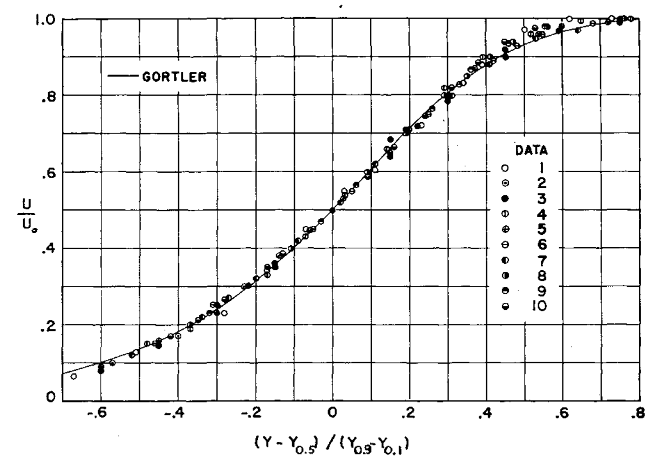

Fig. 1 Dimensionless velocity profile in the half-jet mixing region.

It can be seen that, over a fairly wide range of exit velocities, the different velocity profiles lie very closely along the same curve. This universal curve is best fitted by Gortler's theoretical profile for incompressible jets[6] with his parameter

Table 1 A list of some of the experimental investigations of turbulent jets

Investigation	Date	Nozzle[a] exit shape	Nozzle exit dimensions	Axial distance from exit	Measurement method	Nozzle exit speed
Abramovich[4]	1948	*A*	100 mm	$X/D = 2.5$	...	40 m/sec
Liepmann and Laufer[2]	1947	*R*	60 × 7½ in.	20 cm	Hot wire	59 fps
Laurence[3]	1956	*A*	3½ in.	$X/D = 4$	Pitot pressure	$M = 0.7$
Davies & Fisher[7]	1963	*A*	1 in.	$X/D = 3$	Hot wire	$M = 0.3$
Bradshaw et al.[8]	1963	*A*	2 in.	$X/D = 2$	Hot wire	$M = 0.3$
Maydew and Reed[1]	1963	*A*	3 in.	$X/D = 3$	Pitot pressure	$M = 0.95$
Maydew and Reed[1]	1963	*A*	3 in.	$X/D = 3$	Pitot pressure	$M = 1.49$
Maydew and Reed[1]	1963	*A*	3 in.	$X/D = 3$	Pitot pressure	$M = 1.96$
Present investigation	1964	*A*	4 in.	$X/D = 3$	Hot Wire	140 fps
Present investigation	1964	*A*	4 in.	$X/D = 4$	Hot Wire	140 fps

[a] *A* = axisymmetric, *R* = rectangular.

Received January 7, 1965. The work reported here was incidental to an investigation of jet turbulence and noise under the supervision of H. S. Ribner and was supported by Air Force Office of Scientific Research Grant No. AFOSR 223-64, by National Research Council of Canada Grant No. A2003.

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$\sigma(Y - Y_{0.5})/X$ replaced by $(1.78)(Y - Y_{0.5})/(Y_{0.9} - Y_{0.1})$. The velocity profile in the mixing region of any particular jet can be estimated from the universal curve by determining the distances $Y_{0.1}$, $Y_{0.5}$, and $Y_{0.9}$ at one downstream location. [If these are not known, the line $Y_{0.5}$ vs X may be estimated and the relation

$$Y_{0.9} - Y_{0.1} = 1.78X/\sigma$$

resorted to, using tabulated estimates of σ where available (e.g., Refs. 1 and 2); this is in effect a reversion to the $\sigma(Y - Y_{0.5})/x$ similarity parameter and is only as accurate as the value of σ.]

References

[1] Maydew, R. C. and Reed, J. F., "Turbulent mixing of axisymmetric compressible jets (in the half-jet region) with quiescent air," Sandia Corp., Aero-Thermodynamics Research Rept. SC-4764 (RR) (1963).

[2] Liepmann, H. W. and Laufer, J., "Investigations of free turbulent mixing," NACA TN1257 (1947).

[3] Laurence, J. C., "Intensity, scale and spectra of turbulence in mixing region of free subsonic jet," NACA Rept. 1292 (1956).

[4] Abramovich, G. N., *The Theory of Turbulent Jets* (Technology Press, Cambridge, Mass. 1963), Chap. I, p. 9.

[5] Albertson, M. L., Dai, Y. B., Jensen, R. A., and Rouse, H., "Diffusion of submerged jets," Proc. Am. Soc. Civil Engrs. **74**, 1751 (1948).

[6] Gortler, H., "Berechnung von Aufgaben der freien Turbulenz auf Grund eines neuen Naherungsansatzes," Z. Angew. Math. Mech. **22**, 5 (1942).

[7] Davies, P. O. A. L. and Fisher, M. J., "Statistical properties of the turbulent velocity fluctuations in the mixing region of a round subsonic jet," Univ. of Southampton, Rept. AASU 233 (1963).

[8] Bradshaw, P., Ferriss, D. H., and Johnson, R. F., "Turbulence in the noise-producing region of a circular jet," National Physics Lab. Aero Rept. 1054 (1963).

Catalytic Probe Response to High Atom Flux in a Glow Discharge Shock Tube

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In Ref. 1 we reported on our measurements of heat transfer to a differential catalytic heat gage in shock-tube dissociated flows. The differential heat transfer is proportional to the atom concentration in the flow. Although most of the results followed generally expected trends, a new disturbing feature appeared in some of the measurements. Specifically, at the lower initial pressures in the shock tube, the differential heat transfer was found to vary with time instead of achieving a constant value immediately. At that time, we could envisage this effect as being due to either of two possibilities: first, slow dissociation relaxation in the shock layer of our probe, or secondly, a slow surface reaction rate at these lower pressures. We had pointed out at other times, and there has been some experimental evidence to the effect, that this latter possibility could be ascribed to submechanisms in the phenomenon of surface catalyzed atom recombination. For example, an atom must be adsorbed onto a surface, it must diffuse to an active site where it awaits another atom to recombine with, and then the molecule desorbs. If the time scale for all of these events to occur is of the same order as the delivery rate of atoms in an experiment, it is conceivable that the observed time dependence of the differential catalytic heat-transfer measurements could be reconciled. That is, it is conceivable that the catalytic efficiency of a surface might depend on the atom flux. In our glow-discharge experiments,[2] which are used to determine the catalytic efficiency of surfaces of interest, atoms are delivered to the surface at a relatively slow rate (10^{17}/sec), whereas in our shock-tube experiments they are delivered on the order of 10^{20}/sec. Shock-tunnel flows will deliver atoms to the surface at a rate of about 5×10^{19}/sec. Since one of the major intended applications for our catalytic probe is to measure atom concentrations in hypersonic shock-tunnel test sections[3] in order to establish the nonequilibrum state of the gas flow, it was imperative that we identify the source of the time dependence of our shock-tube measurements. It was clear that we needed an experiment in which a known step function of atoms be delivered to our catalytic surface at a rate of the order 10^{19}/sec with a rise time of order $\frac{1}{2}$ msec or less. Furthermore, it was essential that no gas phase kinetics be present so as to remove that possibility from causing a time dependent reading of our catalytic probe in these new experiments. To solve this problem we conceived the idea of the glow-discharge shock tube (GDST). The details of the construction and method of operation are given in a technical report[4] just published at the Aerospace Corporation. Briefly, the GDST combines an ordinary glow-discharge tube and the shock tube. It is shown schematically in Fig. 1 together with an x-t diagram. The GDST works as follows: first, gas is flowed continuously along the glass tube (4 in. diam, 17 ft long, super-tough pyrex) at 10–30 fps, then, at a given time, the rf energy is suddenly applied at the position indicated by the coil in the sketch, which partially dissociates the gas; when the step function of dissociated gas so produced convects down to within a foot or so of the probe, the diaphragm of the driver section is made to burst with a solenoid-driven plunger, causing a shock to propagate into the predissociated gas. For the weak shocks that we employ ($M_s \approx 2$), neither do the atoms recombine as a result of the increased density nor are any new atoms formed by thermal dissociation. Rather the only effect is to compress and accelerate to high speed the atoms already present in the tube. In our ordinary glow-discharge experiments, despite the fact that we suddenly turn the rf discharge on, we do not get a perfect step function of atoms, because as they convect down the tube at 20 fps, say, the atoms diffuse forward into the undissociated gas producing an atom profile that extends about 2 ft by the time it reaches the probe position. Under the slow flow, the front takes about 100 msec to cross the probe. On the other hand, after they are shocked, two particles on either end of this front cross our probe in about $\frac{1}{2}$ msec. This sharpening of the atom front, which can be seen on the x-t diagram, is one of the major effects sought. We have conducted three types of tests using an initial pressure of 600 μ oxygen and a shock Mach number of 2. In the first, we

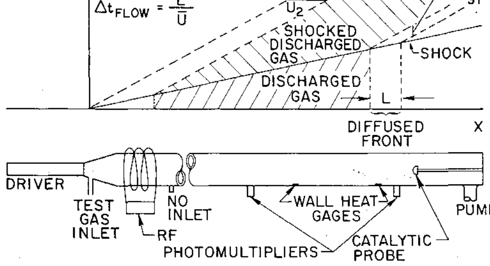

Fig. 1 Glow discharge shock tube; $\bar{U}$ = convective velocity in slow flow; L = length of diffused front in slow flow; V_s = shock velocity and ρ_2/ρ_1 = shock density ratio.

Received December 9, 1964. This work was supported by the U.S. Air Force under Contract No. AF 04(695)-269.

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