$\sigma(Y - Y_{0.5})/X$ 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.]

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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 ($M_s \backsimeq 2$), 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

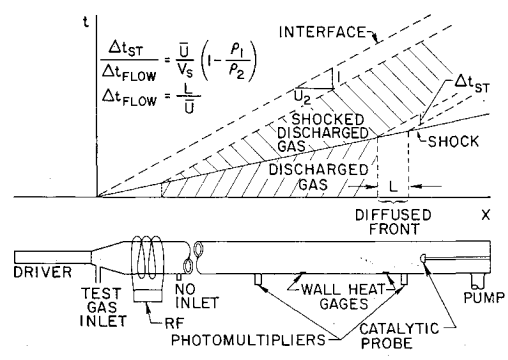

Fig. 1 Glow discharge shock tube; $\bar{U}$ = convective velocity in slow flow; L = length of diffused front in slow flow; V_s = shock velocity and ρ_2/ρ_1 = shock density ratio.

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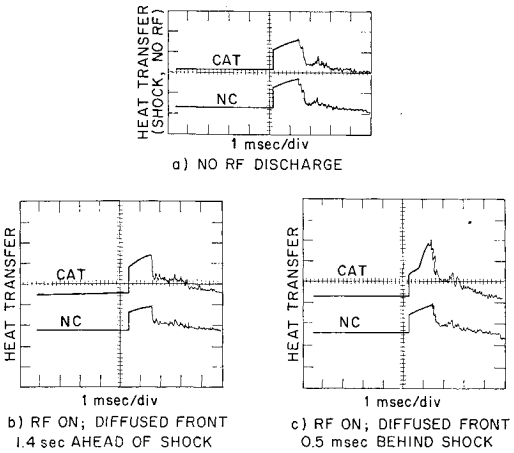

Fig. 2 Heat transfer to catalytic and noncatalytic heat gages with and without rf discharge; $M_s = 2$, $p_1 = 600$ μHg.

established the gas flow and shocked it, but did not turn the rf discharge on. The resultant heat-transfer records to the catalytic and noncatalytic gages are shown in Fig. 2a. Since no atoms were formed, we expect identical records, which is what happened. The slight difference between the two records is due to somewhat different gage sensitivities. The rise with time of the heat transfer during the useful test time is due to attenuation of the shock. This attenuation is of no direct consequence to our experiment. In the second experiment, we turned the discharge on and permitted the front of atoms to pass our probe position before firing the shock. In this way, many of the available sites of the silver oxide catalytic surface could be occupied prior to being exposed to the rapid increase in flux of atoms behind the shock wave. If the surface kinetics follows the change in atom concentration instantaneously on the time scale of this experiment, the heat transfer to the catalytic surface should rise immediately to a higher value than indicated in Fig. 2a (when no rf was applied). This is exactly what happened. The catalytic gage heat-transfer jump across the shock with rf is 50% higher than the no rf case (Fig. 2b), whereas the noncatalytic gage gives a record identical to that of Fig. 2a. The differential heat transfer implies an atom mass fraction of about 3%, which is very close to that which we determine by titration with NO_2.[5]

Finally, the third experiment timed events such that the shock wave arrived at the probe well in advance of the discharged step function gas. In this way we would establish that the rapid response of the surface kinetics was not due to the intentional filling of active sites. For this case, immediately behind the shock, undissociated gas follows so that the initial heat-transfer rises should correspond to those indicated in Fig. 2a. When the front of atoms is convected across the probe, the catalytic heat transfer should rise rapidly. This is precisely what happened, as indicated in Fig. 2c. Again, the noncatalytic gage in this run remained identical to that in the case with no rf discharge.

As a result of these experiments, we conclude that the surface reactions are rapid enough to follow the sudden changes in atom flux, so that the time dependence of differential catalytic heat transfer observed in our shock-tube experiments is not due to slow surface kinetics. With this fact established, and because of the similarity of the atom flux to which the probe has been exposed in these GDST experiments and those to be found in the shock tunnel, we can state that the catalytic probe should behave well as an atom concentration detector in hypersonic shock tunnels. Space does not permit discussion of our method for independently following the atom concentration in these experiments through the use of NO addition[5] (which reacts with the O atoms to produce a glow) and the use of photomultipliers to measure the time history of the glow intensity during the run. It should be stated, however, that the atom concentration histories so determined corroborate the sharpening of the front, as well as the detailed histories of catalytic heat-transfer measurements. Finally, many of the uses for the principle of the glow-discharge shock tube, including the important prospect of measuring gas phase recombination rate temperature dependences are described in Ref. 4.

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Noise of Highly Turbulent Jets at Low Exhaust Speeds

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That the noise of jets increases with the eighth power of the exhaust velocity is not only one of the fundamental results of aerodynamic noise theory, it is also an observed property of jet flows throughout the operational speed range of modern engines. At the higher exhaust velocities characteristic of rocket motors, the eighth-power law gives way to a dependence of the radiated energy on the third power of the exhaust velocity or on the mechanical power of the rocket motor. These eighth- and third-power laws are, perhaps, the only fundamental results one can elicit from the theory of aerodynamic noise relating turbulent flow to the distant sound field it induces. They have become widely used and are verified by experimental study.

Efforts to reduce the noise of engines have therefore concentrated, quite naturally, on the reduction of the jet exhaust speed. The advent of the bypass engine brought along a considerable reduction in the noise level, and these have been developed into the modern fan engines with their high bypass air ratio. These systems develop thrust by exhausting an increased mass of air at a reduced velocity and thereby benefit from a reduction in radiated sound. Engines of higher power must go to still lower exhaust speeds to maintain the same noise levels, and it would appear at first sight that this development could be continued indefinitely, until the discrete frequency sound, generated by the fan that propels the bypass air, becomes the dominant noise of large engines. However, a closer study reveals that this trend cannot be continued until the exhaust noise is reduced to an arbitrarily low level. A fundamentally different source of noise becomes evident, a source that is additional to that of the fan. The way in which this usually concealed source of noise enters the problem is

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