with the perfect gas hypersonic approximations $(D_{eff}/U_e)(dU_e/dx) \simeq 1.1$, $U_\infty/U_2 \simeq 6$, and $\rho_e/\mu_e \simeq \rho_2/\mu_2$, where the subscript 2 designates conditions immediately behind the shock and D_{eff} is an effective model diameter. Equation 4 can be applied when the term in the brackets is greater than 70. This form of the correlation completes the analogy to the subsonic heat-transfer correlations and the power law exponent explains the generally observed weak heat-transfer dependence on model size.

Conclusions

A correlation of blunt model stagnation region heat-transfer data for particle laden hypersonic flows has been developed based on an analogy to the effects of freestream turbulence. Although the exact mechanism for turbulence production has yet to be determined, data correlation procedures indicate that the turbulence intensity is a function of the particle/air mass flux ratio. Insufficient variation in particle diameter is available in the heat-transfer data to determine if, for example, particle number flux is more meaningful. However, the present approach constitutes an improvement over previous correlation procedures because it is based on a phenomenological model, reduces the scatter in the test data, brings together test data from two facilities, properly accounts for the observed heat-transfer insensitivity to model size and, in its full form, provides an asymptotic reduction in augmented heating level as the particle concentration decreases to zero.

The present model was developed using dust laden hypersonic flow heat-transfer data for nonerosive materials so that surface roughness was not a contributing mechanism. It is postulated that the model can be extended to erosion roughened materials with the assumption that the erosion induced roughness elements generate turbulence through vortex shedding. Application of the erosion wind-tunnel results to reentry flight environments requires consideration of particle size effects (i.e. impact frequency) and erosive material contribution.

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Absolute Fluorine Atom Detection by Gasification of Boron Nitride

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Introduction

DISSOCIATION of fluorine, chlorine, and oxygen is known to increase the rates with which they gasify certain solids. Thus, for example, the rates of the F/W, F/Mo,[1] the Cl/Mo[2], and the O/graphite[2] reactions can be easily measured at temperatures below 1000K where the corresponding diatomic molecule reaction rates are negligible. These atom/solid gasification reactions could provide a gravimetric method for atom concentration measurement in flow systems, but at room temperature the atom reactions are so slow that complete reaction is difficult to achieve. This is not the case for the F/BN reaction, which we have employed to develop a gravimetric absolute F-atom detection technique as described in this Note.

Finely divided boron nitride reacts spontaneously with fluorine[3] at room temperature $P_{F_2} < 0.2$ atm according to the reaction

$$BN(s) + 1.5\,F_2(g) = BF_3(g) + 1/2N_2(g) \tag{1}$$

with considerable heat release ($\Delta H°_{298} = -885$ kJ/mole).[4] However, we observe no reaction between dense, hot-pressed BN and F_2 at room temperature ($P_{F_2} \approx 6 \times 10^{-4}$ atm) although rapid BN gasification occurs if the fluorine is dissociated by a microwave discharge. BF_3 and N_2 need not be the only direct product species under nonequilibrium conditions. Some F-atoms may recombine, and BF(g), BF_2(g) may also be produced. Further, the reaction-induced temperature rise may increase the F_2 reaction rate. Therefore, although the F/BN reaction is rapid at room temperature, these side reactions might interfere with gravimetric F-atom concentration measurements. Our results show these problems to be absent under our experimental conditions. Also, limits are obtained on the intrinsic F, F_2/BN reaction rates which establish a wide range of applicability for this technique.

A previous example of F-atom concentration measurement by atom/solid gasification has been reported by Rosner and Allendorf.[1] They employed differences in the rates of atom and molecule reaction with Ti or B at high temperature to infer F-atom concentrations in partially dissociated fluorine. F-atom concentrations may also be measured using chemiluminescent titration with Cl_2[5-7] and spectroscopic techniques.[8] The present method avoids the need for specialized equipment and errors due to atom loss between the experiment of interest and the measuring device, which limit application of these alternate techniques. In fact, the need for measurements at higher total pressure and F-atom concentration, where the chemiluminescent titration fails,[7] motivated the present development.

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Index categories: Lasers; Reactive Flows; Thermochemistry and Chemical Kinetics.

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Experimental

The discharge flow system employed for the present experiments is similar to that described in Ref. 9. Metered Ar/F_2 mixtures pass through an alumina discharge tube where the fluorine is dissociated by a 2450 MHz, *ca.* 70 W microwave discharge. Valves are provided for turning the F_2 flow on and off within 1 sec. The partially dissosciated gas mixture flows through a Pyrex section (location 10-25 cm downstream of the discharge) where pressure is measured with an oil manometer.

Reaction of atomic fluorine with BN was studied by attaching BN specimens to the end of the discharge tube. Their mass was measured to ± 0.02 mg before and after each run with a Mettler H20 semimicro laboratory balance. In separate experiments a thermocouple was used to measure boron nitride specimen temperature during reaction with atomic fluorine. Specimen temperatures never exceeded 500K during the experiments reported here.

Different BN specimen designs were necessary under different experimental conditions. At low flow rates we used a 1-cm-long BN plug which contained six 0.067-cm-diameter holes. The plug was machined from dense Grade A hot-pressed boron nitride obtained from Carborundum Co. Complete reaction of the atomic fluorine was demonstrated by no observable change in the downstream hole diameter after half the boron nitride had been consumed in a series of experiments. This material showed a smooth recession of the surface upon reaction with atomic fluorine. At higher flow rates we used a 6.2-cm-long by 0.60-cm-i.d. BN tube, whose source is unknown. This somewhat porous material developed a rough surface upon reaction with atomic fluoride and absorbed atmospheric vapor as shown by a typical 5-mg mass gain after a 30-min exposure to the atmosphere. Its mass loss was therefore obtained with an accuracy of only ± 1 mg. The fluorine obtained from Argonne National Laboratory had been purified by low temperature distillation and was better than 99.9% pure. Argon (99.998%) was further purified by use of Oxisorb cartridges (MG Scientific Gases Co.), which reduce the O_2 content to *ca.* 1 ppm.

We checked whether BN reacts with F_2 in a separate experiment with a dense BN sample exposed to F_2 at $P_{F_2} \approx 4\times10^{-5}$ atm, $T \approx 510$K in a heated aluminum tube. The mass loss flux from the BN specimen was 5.1×10^{-7} g/cm^2 sec, which implies an intrinsic reaction probability ϵ_{F_2} (BN)$=2.4\times10^{-3}$ at 510K. The value ϵ_{F_2} (BN)$<5\times10^{-6}$ at 300K was deduced from an experiment which showed a negligible (<0.06 mg) mass loss at room temperature.

Results

Our results are presented in terms of the apparent F_2 dissociation efficiency, η_{app}, which is the ratio of the measured BN gasification rate to that which would result under complete reaction with F and F_2 to produce BF_3. Since F_2 presumably does not react, η_{app} reflects the influence of three processes: dissociation in the discharge, recombination on Al_2O_3,and reaction with BN, with respective efficiencies η_D, $\eta_{Al_2O_3}$, η_{BN}.

$$\eta_{app} = \eta_D \cdot \eta_{Al_2O_3} \cdot \eta_{BN} \qquad (2)$$

From previous chemiluminescent titrations[7] we expect $\eta_D \approx 0.9$. Approximate valves of $\eta_{Al_2O_3}$ are computed from the known[10] recombination probability $\gamma_F(Al_2O_3) = 6.4 \pm 1.1\times10^{-5}$, and the discharge tube transit times $\tau_{Al_2O_3}$. We will show that the volumetric gas flow rate and BN duct length are sufficient to determine η_{BN} in accord with diffusion controlled rates of reaction.

Figure 1 presents our measurements at low flow rates, where $\eta_{BN} = 1$ and $\eta_D \approx 1$. The plot of log η_{app} vs $\tau_{Al_2O_3}$ gives good agreement with that computed for $\eta_{Al_2O_3}$, which is shown by the line. The indicated errors in $\tau_{Al_2O_3}$ are mainly due to uncertainty in the computed pressure drop across the BN plug. These results confirm the previous measurements[10] of $\gamma_F(Al_2O_3)$ at the higher F-atom concentrations that pevailed here (1-2$\times10^{16}$ atoms · cm^{-3}). Also, no evidence can be found in these experiments for interference with the F/BN reaction by recombination, production of product species other than BF_3, or reaction with F_2. We use $\eta_D = 1$ although chemiluminescent titrations[6,7,10] have never given $\eta_D > 0.92$. Higher dissociation efficiency might be expected here because discharge residence times are *ca.* 60 msec, compared to less than 1.7 msec in the titration experiments.

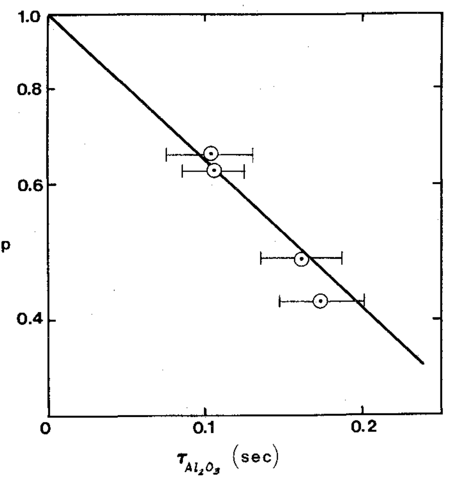

Fig. 1 Comparison of apparent fluorine dissociation efficiencies. The line shows values expected with complete dissociation at the discharge and atom loss according to known F/Al_2O_3 recombination kinetics. The data points were measured by reaction with boron nitride.

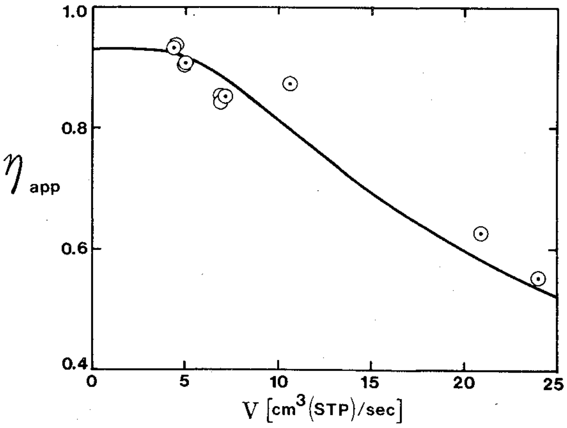

Fig. 2 Comparison of apparent fluorine dissociation efficiencies (data points) with values predicted for diffusion controlled F/BN reaction.

At sufficiently high flow rates, diffusive transport in the cylindrical duct of length *L* and diameter *d* limit F-atom reaction with BN to

$$\eta_{BN} < 1\text{-}\exp(-4NuDL/Ud^2) \qquad (3)$$

where *U* is the gas velocity, *D* the F/Ar binary diffusivity, and *Nu* the average diffusional transfer coefficient (3.66 for fully developed laminar flow). The equation is only approximate, since constant property flow is assumed,[11] while pressure drops and temperature changes occur across the BN tube in our experiments. Nevertheless, since *D/U* is pressure independent and only weakly temperature dependent ($D/U \propto T$ 0.7), we may take approximate agreement with Eq. (3) to indicate diffusion controlled reaction. Then, a limit on the intrinsic chemical reaction rate constant, k_w, or reaction probability, $\epsilon_F(BN)$, can be obtained from the requirement for diffusion control[11]

$$k_w \cdot d = \epsilon_F(BN) \cdot c \cdot d/4 >> Nu \cdot D \tag{4}$$

where c is the F-atom mean thermal speed.‡ Figure 2 illustrates our data and the results predicted by Eq. (3). We use $D=0.39$ cm^2/sec at $T=100°C$, $P=1$ atm (calculated from Svehla parameters[12]), $\overline{Nu}=3.66$, and assume $\eta_D \cdot \eta_{Al_2O_3}=0.93=$ constant to compute the values shown by the line. These results show the reaction to be diffusion controlled. Thus, for diffusion limited experiments at or above room temperature, we obtain the useful criterion for complete reaction (>99% F-atom consumption)

$$V[\text{cm}^3 \text{ (STP) /sec}] < 1.6L[\text{cm}]$$

Discussion

The principle difficulty in the use of F/BN gasification to measure F-atom concentrations is control of sample temperature to avoid F_2 reaction. This can easily be achieved by limiting BN consumption to less than 0.5% of the specimen, as was the case in most of our experiments. Then the reaction enthalpy cannot heat a specimen initially at room temperature to more than 500K. Temperature control might be more difficult with small BN specimens and higher F-atom concentrations. In this case it would be possible to infer F-atom concentrations from measurements of transient specimen temperature.

The agreement between F-atom concentrations measured by chemiluminescent titration and by reaction with boron nitride leads us to conclude that the present gravimetric method is accurate to at least ± 10%. Atom recombination and production of species other than BF_3 do not interfere with this method. The F_2/BN reaction may be ignored at room temperature but becomes significant near 500K. This new method permits F-atom concentration measurements above *ca.* 10^{15} cm^{-3}, where systematic errors[7] appear in the chemiluminescent titration method. Calibration of spectroscopic techniques and *in situ* measurement of concentration gradients (e.g., in gas dynamic hydrogen fluoride laser nozzles) are other suggested applications of the F/BN gasification reaction.

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‡This condition is met if $\epsilon_F(BN) >> 0.1$ for these experiments.

On the Application of Tension to Compliant Membranes

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THE feasibility of achieving drag reduction by the use of compliant surfaces in turbulent boundary layers is currently a topic of considerable interest. Although a substantial experimental effort has been reported and significant drag reductions have been noted, the results, to date, have been inconclusive.[1-4] With support of the NASA Langley Research Center, NBS has undertaken to investigate the merits of the compliant surface as an effective method for drag reduction. An important consideration in such an investigation is that the surface motion be adequately specified, and it is necessary, therefore, not only to assure that the tension and membrane mass per unit area be specified but that the applied tension be uniformily distributed and continuously monitored. In addition, the effect of air impedance on the normal modes of the surface motion must also be considered. In the design of an appropriate surface, a method of applying tension that meets these conditions has been developed and evaluated, and it is the purpose of this note to describe the method and the results of this initial evaluation.

A square frame sized to allow a free membrane area 1.24 m on each side was constructed of aluminum angle material. This frame with the membrane attached is to be inserted as a section of a larger boundary-layer plate for use in the wind-tunnel tests on drag reduction. Solid aluminum webs were added at each corner of the frame so as to divide each side of the angle frame into a separate chamber adjoining each edge of the free-membrane area as shown in Fig. 1. Teflon tape was placed along the edges under the membrane to reduce friction. Applying suction equally to opposite chambers of the frame permits the membrane tensions in two directions (x and y) to be adjusted independently by varying suction in the two pairs of opposite chambers. The uniformly distributed chamber pressure, which can be monitored by pressure taps and transducers, enhances uniformity of the tension applied along each edge of the free membrane. This method also has the advantages that tension can be controlled and monitored at a remote station (outside the wind tunnel), and a very smooth membrane surface without wrinkles can be obtained.

The perimeter of the membrane over each chamber is trapezoidal in shape, with an aspect ratio sufficiently large that the tension T may be computed from an expression for the (approximately uniform) static displacement η_0 of the longitudinal centerline of the trapezoid

$$T = \Delta p b^2 / 8\eta_0 \tag{1}$$

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