A simple method is described for measuring material erosion by reaction with water vapor under high-speed flow conditions, with H₂O partial pressures, velocities, temperatures, and erosion rates representative of those experienced in gas turbine engines. A water vapor jet is formed by the feeding water at a controlled rate into a capillary inside a tube furnace, where the large expansion of vaporization within the confines of the capillary accelerates the jet. With modest flow rates of liquid water, steam jets with temperatures up to \(~1400\) C and velocities in the range 100–300 m/s have been achieved. The partial pressure of water vapor in the 100% steam jet is the same as in an industrial turbine operating at 10 atm total pressure with 10% water vapor. In preliminary experiments with SiC, erosion rates of the order of 1 μm/h have been observed.

1. Introduction

HIGH-TEMPERATURE metallic and nonoxide structural materials in gas turbine engines rely on protection from oxidation by oxide coatings. In some cases, these form naturally from the role of the microstructures of the coatings, and from pure forms of the compounds that constitute the coatings. Conventional preparation and from well-controlled comparative data from complex coatings is clear.

However, in combustion environments, which contain a large fraction of water vapor, the protection is dramatically reduced by reaction of the water vapor with the oxide to produce volatile oxy-hydroxide species. In the case of silica, the following reactions occur, with relative importance being dependent on the temperature/pressure ranges:

\[
\text{SiO}_2(s) + \frac{1}{2}\text{H}_2\text{O}(g) \rightarrow \text{SiO(OH)}(g) + 1/4\text{O}_2(g) \tag{1}
\]

\[
\text{SiO}_2 + \text{H}_2\text{O}(g) \rightarrow \text{SiO(OH)}_2(g) \tag{2}
\]

\[
\text{SiO}_2(s) + 2\text{H}_2\text{O}(g) \rightarrow \text{Si(OH)}_4(g) \tag{3}
\]

Several studies have shown that reaction (3) is dominant at temperatures up to \(~1200–1400\) C, with reaction (2) becoming more significant at higher temperatures.

Similar reactions occur for all oxides, albeit with reaction rates differing by many orders of magnitude. This leads to erosion of the outer surface of the oxide coating and a change from parabolic oxidation kinetics with weight gain to linear kinetics with weight loss. After an initial period of increasing oxide thickness, a steady-state condition of constant oxide thickness is approached, in which rates of material loss at the outer surface and oxidation at the interface of the oxide and the base material are equal.

The time to reach steady state, the steady-state recession rate, and the limiting oxide thickness are all very sensitive to flow conditions, both pressure and gas velocity. With the especially strong dependence on gas velocity, conditions typically achieved in laboratory experiments give erosion rates many orders of magnitude slower than in real gas turbine engines (and other engines including rocket and combined cycle engines). It is perhaps for this reason that the role of water vapor erosion as the life-limiting mechanism in SiC and Si₃N₄ engine components was for many years overlooked in favor of other mechanisms such as creep and oxidative strength degradation that dominate in less aggressive laboratory conditions.

However, from the references mentioned above, which include burner rig and long-term engine testing, the dominant role of water vapor in combustion environments is clear.

This realization has motivated efforts to develop environmental barrier coatings consisting of complex oxides that are more resistant than SiO₂ to water vapor corrosion. However, the data on corrosion rates for other oxide compounds are very limited. The difficulty of measuring the response of developmental coating materials without going to extremely costly engine tests remains a barrier to development. Moreover, without well-controlled comparative data from complex coatings and from pure forms of the compounds that constitute the coatings, it is often difficult to distinguish effects of the compounds themselves from the role of the microstructures of the coatings.

The purpose of this paper was to demonstrate a simple approach for overcoming this barrier, using a jet of high-temperature water vapor to generate flow conditions with H₂O partial pressures, velocities, temperatures, and erosion rates representative of those experienced in turbine engines. The jet is formed by feeding water at a controlled rate into a capillary tube inside a tube furnace, where the large expansion of vaporization within the confines of the capillary accelerates the jet. With very modest flow rates of liquid water, steam jet velocities typical of flow rates in industrial turbines can be achieved (e.g., flow of water at rates in the range 1–2 mL/min into a 1-mm-diameter capillary creates jets with temperatures between 1100 C and 1300 C and 1 atm pressure with a velocity in the range 160–300 m/s). The partial pressure of water vapor in the 100% steam jet is the same as in an industrial turbine operating at 10 atm total pressure with 10% water vapor. The test set-up builds on work reported...
earlier by Ferber and Lin\textsuperscript{33} who used a capillary to produce a steam jet, although with gas velocities an order of magnitude lower (35 m/s). More recently, Sudhir and Raj\textsuperscript{34} used a steam jet in a different configuration to measure oxidation weight changes in silicon nitride at velocities up to 0.35 m/s.

The area of the test sample exposed to high-velocity steam in these experiments is small (a few millimeters diameter). Whereas this would be a disadvantage for measuring degradation in the conventional manner through weight changes, the presence of an adjacent unexposed reference surface makes possible a more direct and informative approach by measurement of surface recession.

II. Experimental Procedure

The test set-up, shown in Fig. 1, uses a tube furnace with a mullite tube (length 1 m) and flanges that accommodate several inlet and outlet attachments for gas and water supply, as well as an attachment to hold an alumina tube inside the furnace. The alumina tube extends to the center of the hot zone of the furnace and serves as specimen holder. A quartz glass capillary with a hole of diameter 1 mm is mounted along the center of the alumina tube and connects through the inlet flange to a peristaltic pump, which feeds ultrahigh purified liquid water into the capillary. As the water enters the hot zone of the furnace, it evaporates and accelerates to form a jet of high-temperature steam. The surrounding atmosphere (between the emerging jet and the mullite furnace tube) is flowing argon, which enters through a second inlet in the same flange at a rate of 4 L/min, giving a gas velocity \(0.1\) m/s in hot zone. The argon and the water vapor are extracted through a single outlet and passed through a condenser before being released into the atmosphere.

The temperature of the steam jet emerging from the end of the capillary was measured using a thermocouple (type R), routed through the alumina tube and held in front of the capillary tip. A set of calibration tests were carried out with the thermocouple bead placed about 1 mm from the tip of the capillary, at the same position the test specimens were mounted during the experiments. The calibration test matrix included water flow rates between 1 and 6 mL/min and furnace temperatures between 1300°C and 1500°C. The temperatures were recorded after reaching steady state before and after the water was turned on, as well as after the water was turned off, to ensure that the thermocouple did not degrade during the experiments.

The average velocity, \(v_{av}\), of the steam jet was estimated using the ideal gas law

\[
v_{av} = \frac{m R T}{A MW P}
\]

where \(m\) is the mass flow rate, \(R\) the universal gas constant, \(T\) the temperature of the jet, \(A\) the cross-section area of the capillary, \(MW\) the molecular weight of water, and \(P\) the pressure at the exit of the capillary. The exit pressure was taken to be approximately equal to the ambient pressure (1 atm), an assumption that was confirmed to be accurate to within \(<0.2\%\) from CFD analysis (Appendix A). The velocity along the centerline of the jet decreases beyond the capillary exit, although the decrease is expected to be small over a distance of \(~5\) times the capillary diameter.

The water vapor jet was directed onto the leading edge of a sharp wedge-shaped test specimen as shown in Fig. 1. The test material was polycrystalline SiC produced by chemical vapor deposition (Morton International Inc., Woburn, MA). The test specimens were prepared by grinding and polishing blocks of dimensions 10 mm \(\times\) 10 mm \(\times\) 1 mm to form sharp wedges with an included angle of 6° (Fig. 1(b)). In this configuration, the sharp edge of the specimen was aligned with the center of the jet, so that the jet was divided into two equal streams flowing almost parallel to the two wedge faces. During initial set-up of the test, another configuration was investigated with the jet incident on a flat polished surface inclined at an angle of 45° to the flow. While this was also convenient for producing measurable recession, the flow conditions adjacent to the specimen surface are more complex.

The specimens were mounted in an alumina holder and locked in place in front of the capillary, with an alumina tube being used to hold and align all components. Photographs taken before and after each test were used to confirm that no parts shifted during the experiment. Three combinations of water flow rate and duration were chosen from the initial set of calibration data for furnace temperature of 1500°C: 1.87 mL/min for 20 h;
1.87 mL/min for 12 h; and 1 mL/min for 20 h. After the experiments, the depths of erosion were measured by profilometry and optical interferometry.

III. Results

(1) Temperature Calibration

Results of the temperature calibration are summarized in Fig. 2. In the set-up used in these experiments, the length of capillary tube in the hot zone of the furnace is not sufficient to allow equilibration of the temperatures of the water vapor and the furnace atmosphere, so that the temperature of the vapor jet is lower than the furnace temperature by an amount that is sensitive to the flow rate. Moreover, because this temperature difference increases with increasing flow rate, the velocity of the vapor jet at given furnace temperature does not increase monotonically with the water flow rate (Fig. 2(b)).

An estimate of the position at which the liquid water vaporized could usually be obtained from a slight discoloration visible on the inside of the capillary tube after the test run (from trace amounts of contaminants in the water). The distances between this position and the exit of the capillary were approximately 12 and 17 cm for flow rates of 1.0 and 1.87 mL/min, corresponding to a residence time of the accelerating gas in the capillary of the order of $10^{-3}$ s.

(2) Recession Measurements and Observations

A sharp wedge-shaped SiC test sample was observed as shown in Fig. 3(a), after exposure for 20 h in a jet of mean velocity 260 m/s and temperature 1160°C (furnace temperature 1500°C). Severe recession occurred both in the position of the leading edge and optical interferometry.

Examination by SEM and EDS analysis indicated that there was a continuous SiO$_2$ layer outside the region of jet flow. However, there was no detectable evidence for the oxide layer within the deep grooves, while in the central region of the jet flow, discontinuous patches of thin oxide were detected. Elementary maps of silicon, oxygen, carbon, and aluminum from the region of Fig. 3(c) are shown in Fig. 4 (note the absence of oxygen along the grooves, reduced oxygen signal at the central region of jet flow, and complementary regions of high and low oxygen and carbon signals). The presence of a small concentration of aluminum outside the region of the jet flow is indicative of formation of volatile aluminum oxy-hydroxides by the reaction of aluminum with oxygen along the grooves (originally a straight line) and in grooves along the initial flat polished faces of the wedge. The positions of the deepest grooves coincide with flow at the periphery of the water vapor jet.

From the profilometer data shown in Fig. 3(b), the recession depth in the central region of the jet flow is $\sim 9$ μm, and is roughly constant within a distance of $\sim 4$ mm from the leading edge. The grooves at the edge of the flow are deeper by a factor of 3 or more near the leading edge ($\sim 27$ and 30 μm) and become shallower with increasing distance downstream. The formation of grooves of this depth on both sides of the wedge-shaped test samples would cause the leading edge of the wedge to recede by $\sim 500$ μm. This is close to the observed recession of the leading edge in Fig. 3(c), thus indicating that material removal in this region is predominantly from the flat faces of the wedge rather than from the stagnation point at the leading edge itself. This conclusion is further supported by the observation that the leading edge remains sharp in the grooves.

Independent measurements of recession depths and oxide thickness were obtained using optical interference microscopy. Three sets of fringes are visible in the white light interference micrograph shown in Fig. 3(d); one set is from interference between reflections from the microscope reference mirror and the top surface (oxide) of the test specimen; a second set from interference between the reference mirror and the SiO$_2$–SiC interface; and the third set from interference between the top of the oxide layer and the oxide–SiC interface. For a flat surface (i.e., before exposure to the water vapor jet), the first two sets of fringes would be straight and horizontal. In Fig. 3(c), the downward displacement of these fringes, visible in Fig. 3(d), is proportional to the recession depth of the surface, while the separation of the two sets of fringes is proportional to the thickness of the oxide layer. The near-vertical fringes from interference between the top and bottom of the oxide layer also give a measure of the layer thickness. Measurements from these fringes as well as measurements from interference micrographs obtained using monochromatic light indicated that the thickness of the oxide layer is $\sim 4$ μm outside the region impacted by the jet (right side of the micrograph) and the thickness decreases continuously toward the center of the groove, where the oxide thickness is below the detection limit of the interference measurements ($\sim 30$ nm). In the central region of the jet flow, a thin oxide layer (thickness $<200$ nm) was detected in patches separated by regions where no oxide was detected.

Higher magnification views of the specimen in Fig. 3 are shown in Fig. 5. Large differences in the surface texture are evident in various regions: the region outside the vapor jet, which is covered with a layer of glassy SiO$_2$, is relatively smooth, whereas the region within the grooves is much rougher and pitted, with no evidence of glassy SiO$_2$ detected either from the appearance of the SEM image or from EDS analysis. In the central region of the vapor jet, a mixture of surface textures are evident, circular depressions with rough pitted surfaces surrounded by a smoother thin film of glassy SiO$_2$. Many of the circular depressions showed radial texture that might suggest an association with cristobalite spherulites. However, no evidence of cristobalite crystals was seen in the pitted surfaces.
Erosion patterns similar to Fig. 3 were observed under several conditions of jet velocity and temperature, although the relative depths of the central region and the edge grooves varied with conditions. At lower velocity (160 m/s) and higher temperature (1350°C), the side grooves were not as distinct, while at high velocity their depth increased with velocity and exposure time. However, in all cases, regions similar to Fig. 5(a) were observed in the side grooves, with rough, pitted surfaces and no evidence of glassy SiO₂ detectable by SEM imaging or EDS analysis. Similar rough pitted surfaces were also observed in the tests in which the jet was incident on a flat polished surface inclined at an angle of 45° to the flow. An example is shown in Fig. 6(a).

IV. Discussion

(1) Flow Conditions in Water Vapor Jet

The main characteristics of the flow conditions in the water vapor jet can be deduced from standard fluid dynamics relations. Within the capillary, the flow is characterized by the Reynolds number\(^3\):

\[
Re_d = \frac{\rho d v}{\mu}
\]

where \(v\), \(\rho\), and \(\mu\) are the velocity, density, and viscosity of the fluid, and \(d\) is the capillary diameter. The flow is laminar for low values of \(Re_d\) with the onset of turbulence occurring at \(Re_d = 2300\) and fully developed turbulent flow at \(Re_d > 10000\). For the range of conditions of the water vapor jet at temperatures up to \(\sim 1400°C\) (\(d = 1\) mm, \(\rho \sim 1.3 \times 10^{-4} \text{ g/cm}^3\), \(\mu \sim 5 \times 10^{-4} \text{ g/cm·s}\), and \(v < 300 \text{ m/s}\)), Eq. (6) gives \(Re_d < 1000\). Therefore, the flow at the exit of the capillary is laminar in all of the experiments.

The fluid velocity for laminar flow in a tube varies across the diameter of the tube, approaching a steady-state parabolic profile after flowing a distance greater than the hydrodynamic entry length, \(x_o\). For a fluid injected into the tube with uniform velocity profile and flowing with uniform mean velocity, \(x_o\) is given by\(^2\):

\[
\frac{x_o}{d} \approx 0.05Re_d
\]

With \(d = 1\) mm and \(Re_d < 1000\), as in the present experiments, Eq. (7) gives \(x_o < 50\) mm. The observations in Section III(1) indicate that evaporation occurred at a distance of \(\sim 120–170\) mm from the exit of the capillary. At the evaporation position,
the velocity profile would be expected to be uniform. Therefore, if flow between the evaporation position and the exit were to occur under isothermal conditions, the steady-state parabolic profile would be approached, for which the maximum velocity (at the center of the jet) is double the average velocity. However, in these experiments, the temperature of the water vapor increases by a factor \( \approx 4 \) between the evaporation point and the exit, resulting in a corresponding increase in average velocity. The velocity profile at the exit in this case is dependent on the variation of gas temperature along the capillary and would be expected to be much more uniform than for the steady-state case. In the absence of a detailed analysis of the velocity profile, the average velocity will be used in the analysis here.

As the water vapor jet exits the capillary, shear forces from interaction with the surrounding atmosphere (slowly flowing argon gas, velocity \(<0.1\, \text{m/s}\)) generate turbulence around the periphery of the jet as depicted in Fig. 1(c), while the central region remains laminar. The intersection of this free-stream turbulence with surface of the test specimen corresponds with the location of the eroded grooves in Fig. 3. This observation is consistent with the expectation that mass transfer (of the volatile reaction products) would be more rapid through the boundary layer in a region of turbulent flow than in the laminar flow region in the central area of the jet.

As the laminar region in the center of the jet flows along the specimen surface, a boundary layer develops adjacent to the surface, characterized by the Reynolds number:\(^{(2)}\):

\[
Re_x = \frac{\rho x_1 V_0}{\mu}
\]

(8)

where \( x_1 \) is the distance from the leading edge (Fig. 1(c)). The flow remains laminar for \( Re_x < 5 \times 10^7 \). Within the region of interest (\( x_1 < 4\, \text{mm} \)), Eq. (8) gives \( Re_x < 1000 \), indicating that the flow remains laminar within this region. Under these conditions, the thickness of the boundary layer that controls diffusion of volatile reaction products (and hence erosion rate) is given by:\(^{(5)}\):

\[
\delta = \frac{1.5 x_1}{Re_x^{1/2} Sc^{1/3}}
\]

(9)

where \( Sc \) is the Schmidt number (defined in Appendix B). Under the range of conditions of these experiments, the boundary layer thickness within 4 mm of the leading edge is always \(<0.2\, \text{mm} \) (see Appendix B). Therefore, the boundary layer on the specimen surface along the centerline of the jet remains confined within the jet (radius 0.5 mm).

(2) Comparison of Water Vapor Jet with Hydrocarbon Combustion: The Silica System

Opila et al.\(^{(5,8)}\) have provided a comprehensive analysis of the behavior of silica-forming materials (SiC and Si\(_3\)N\(_4\)) in flowing gas containing water vapor, under conditions where reaction to form Si(OH)\(_4\) dominates at the outer surface and the reaction rate is limited by diffusion of the reaction product through a laminar boundary layer. This analysis involved use of a correlation function for the Sherwood number for flow over a flat plate, which relates the mass flow rate of the reaction product to the Reynolds number and Schmidt number (hence to velocity, pressure, and viscosity of the flowing gas), the diffusion coefficient, and the equilibrium reaction product concentration at the outer surface. From these results, combined with analysis of the oxidation reaction at the SiC–SiO\(_2\) interface, the following expressions were derived for the steady-state erosion rate, \( \dot{y}_L \), the limiting oxide thickness, \( x_L \), and the time, \( t_L \), to achieve steady state:

\[
\dot{y}_L = C_1 \frac{V^{1/2} P_{H_2O}^2}{\mu^{1/2}}
\]

(10)
\[ x_L = C_2 \frac{P^{1/2}}{P_{\text{H}_2\text{O}}} v \]  
\[ t_L = C_3 \frac{P}{P_{\text{H}_2\text{O}}} \]

where \( v \) is the gas velocity, \( P_{\text{H}_2\text{O}} \) is the partial pressure of water vapor, \( P \) is the total pressure, and \( C_1, C_2, \) and \( C_3 \) are constants dependent on gas properties, reaction enthalpy, and temperature. Test data for recession of SiC from several facilities (high-pressure burner rig (HPBR) and synthetic combustion gas furnace) were correlated with these expressions and used to calibrate the constants \( C_1, C_2, \) and \( C_3 \) at a temperature of 1316°C. The values thus obtained were \( C_1 = 0.18, C_2 = 0.615, C_3 = 1.71 \), with units of pressure in atm, \( v \) in m/s, \( t_L \) in hours, \( x_L \) in \( \mu \text{m} \), and \( y \) in \( \mu \text{m/h} \). The results from Eqs (10–12) with these calibrated constants are plotted in Fig. 7 in terms of gas velocity for several combinations of total and partial pressures.

Industrial turbines typically operate at 10 atm total pressure, with combustion gases containing \( \sim 10\% \) water vapor. Therefore, the partial pressure of water vapor is equivalent to that in a 100\% steam jet at 1 atm pressure. However, the erosion rate at given gas velocity depends also on the total pressure (Eqs (10–12)), at least within the regime where the erosion is controlled by the transport of the reaction product through a laminar boundary layer. This dependence on total pressure, which enters via its influence on the diffusion coefficient for the reaction product through the boundary layer as well as the Reynolds number, makes the water vapor jet more severe than the combustion environment at given gas velocity and equivalent partial pressure of \( \text{H}_2\text{O} \).

Also shown in Fig. 7 are operating conditions for various test configurations and real gas turbine engines taken from Opila (who plotted these equations in a different form, as contour maps for hydrocarbon combustion in terms of velocity and total pressure). It is apparent that the water jet provides erosion conditions (steady-state recession rates, limiting oxide thicknesses, and time constant) close to those of the turbine engine, whereas even sophisticated burner rig facilities (Mach 0.3 burner rig and HPBR) do not achieve the conditions in an industrial gas turbine, the steady-state erosion rates are smaller by a factor of 10–100, the limiting oxide thicknesses are larger by a factor of 10, and the times taken to achieve steady state are longer by a factor of 100. The conditions in laboratory furnaces, either with flowing gas or in a special high-pressure furnace, are many orders of magnitude further from the turbine conditions.

Closer examination of Fig. 7 suggests limits to the ranges of pressure and temperature over which this erosion mechanism applies. At low gas velocities and pressures typical of laboratory...
At the other extreme of high velocity and pressure, as experienced in industrial gas turbines, the time to reach steady state is only a few minutes, the erosion rates are high (~1 μm/h) and the oxide thickness is very small (<0.1 μm). Similar erosion rates and oxide thicknesses were observed in the central laminar region of the water vapor jet in Section III. Conditions are even more severe in H₂/O₂ rocket combustion environments, which experience higher pressures and velocities of water vapor (and higher temperatures), as indicated in Fig. 7. In these cases, the small oxide thickness (<10 nm in Fig. 7(b)) may lead to breakup of the oxide layer (as possibly seen in the turbulent region of the water vapor jet in Figs. 5(b) and 6(a)) and a change in the rate-controlling mechanism from volatility of SiO₂ to the direct reaction of SiC or Si₃N₄ with water vapor. Several possibilities were proposed by Opila: (i) rate controlled by reaction of SiC (or Si₃N₄) with water to give SiO₂, with the oxide being swept away as soon as it forms, (ii) “active” volatilization similar to the active oxidation that occurs for SiO₂ formers at low partial pressures of O₂, where SiO(g) is formed rather than SiO₂. In this case, an analogous reaction would be SiC reacting directly with water vapor to give Si(OH)₄(g), without the intermediate SiO₂ formation step. Evidence for a transition in behavior to a direct reaction was reported for Si₃N₄ vanes after exposure in industrial turbines. The observations in Figs. 5(b) and 6(a) of deeply pitted surfaces in regions of turbulent flow of the water vapor jet are suggestive of a transition in mechanism. Also shown for comparison in Fig. 6(b) is erosion damage on the surface of an SiC test specimen exposed to high-speed H₂/O₂ combustion products from a rocket nozzle. A similar rough surface is evident with pitting at multiple scales. Even if a very thin oxide layer exists in these cases, with thickness below the detection level of SEM analysis, it is clear that the erosion process is more complex than a simple model of diffusion through a laminar planar boundary layer.

Because these conditions cannot be readily obtained in a laboratory environment, there is very little understanding of the details of the mechanism. However, there is evidence for highly accelerated erosion rates in this regime. The upper limit for erosion rate in this case is given by the Langmuir equation for free evaporation into a vacuum. This limit is indicated in Fig. 7(a). It is evident from Fig. 7(a) that extrapolation of Eq. (10) to conditions of H₂/O₂ rocket engines, where the water vapor pressure is substantially >1 atm, gives erosion rates approaching the Langmuir limit. Extrapolation for conditions of the water vapor jet (pH₂O = 1 atm) with laminar flow indicates that a significantly higher jet velocity (~10⁵ m/s) would be required to reach the Langmuir limit.

### 3 Comparison with Measured Recession Rates
Along the line x₁ in Fig. 1(c), where the flow is laminar, the measured recession rates can be compared with the analysis summarized in the previous sections. Two conditions of velocity and temperature were used in the experiments: (A) velocity of 260 m/s at temperature of 1160°C; and (B) velocity of 160 m/s at temperature of 1350°C.

The temperature dependence (Eq. (10)) enters through the parameter C₁, which can be written in the form

\[ C₁ = β T^n \exp(-\Delta H/R T) \]  

where the exponent n is close to −1/4, ΔH is the reaction enthalpy of the volatile species (in this case Si(OH)₄), and β is a temperature-independent function of molecular weights, collision cross sections, viscosity, and the length dimension that appears in the Reynolds number for flow over the specimen surface (see Appendix B). The temperature variation due to the term \( T^n \) is negligible compared with the influence of uncertainties in the exponential term. Thermodynamic measurements by Jacobson et al. over the temperature range 1000–1400 K, within which Si(OH)₄ is the dominant reaction product, give ΔH = 54.6 kJ/mol, whereas the HPBR erosion data used in the calibration of the constant C₁ in Eq. (10) gave ΔH = 108 kJ/mol, a result that was interpreted as implying the presence of appreciable amounts of SiO(OH)₂ as well the predominant Si(OH)₄. Steady-state recession rates predicted from Eqs (10) and (13) with the latter value of activation energy and with the calibration at \( T = 1316°C \) mentioned above are shown in Fig. 8 at the temperatures of the water jet experiments.

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"O. Sudre, unpublished work on SiC composite exposed to testing at Cell 22 facility at NASA Glenn Research Center."
Also shown in Fig. 8 are the measured recession rates. The recession rates on the line $x_1$ in Fig. 1(c) ($0.5-0.8 \, \text{mm/h}$ for condition A and $0.6-0.7 \, \text{mm/h}$ for condition B) were smaller by a factor of 2 to 3 than the predicted values, while the recession rates in the grooves at the turbulent periphery of the jet were slightly higher than the predicted value for laminar flow ($\sim 1.5 \, \text{mm/h}$). These differences likely relate to different flow conditions in the HPBR tests used to calibrate the constant $C_1$ in Eq. (10): (i) the test surfaces in the HPBR tests were oriented at an angle $45^\circ$ to the flow, whereas those in the present experiments were parallel to the flow; and (ii) the gas temperatures in the HPBR tests were higher by $100^\circ \text{C}$ than the measured specimen temperatures used in the calibration, whereas the temperatures referenced in the present tests were measured values for the water vapor jet. If the calibration from the HPBR tests were to be referenced to the gas temperature rather than the measured test specimen temperature ($1316^\circ \text{C}$), the predicted erosion rates at the temperatures of the water jet tests would be lowered by approximately 40% (dotted lines in Fig. 8), giving close agreement with the measured erosion rates for condition A and reducing the discrepancy for condition B. Additional uncertainty is introduced through differences in the length parameter in the Reynolds number and Sherwood number in Eqs (B-1) and (B-2) and the likelihood that the water vapor jet contains some Si(OH)$_4$ from reaction with the capillary wall, which would act to retard the volatilization reaction on the test specimen surface. Given these uncertainties, the measured recession rates appear to be reasonably consistent with the analysis of Opila et al.$^5,8$

**V. Conclusions**

The method demonstrated here provides a means for efficient laboratory scale studies of corrosion of materials and coatings by water vapor, under conditions that are representative of the
gas velocity, partial pressure, and temperatures of gas turbine engines. The configuration with a sharp wedge-shaped test specimen appears to be suitable for quantitative analysis of mass transport through a well-controlled boundary layer. Along the centerline of the vapor jet, the conditions are laminar and analytical correlation solutions are available. Around the periphery of the jet, free stream turbulence creates much higher mass transfer conditions (and hence erosion rates), and possible transition in erosion mechanism. The presence of two regions with well-defined sets of conditions in the one test is a useful feature. Further quantitative analysis of both regions would be possible if the experiments were to be combined with detailed computational fluid dynamics analysis to assess the variation of velocity within the jet (radial and axial) and diffusion of reactants away from the surface in the turbulent region.

Acknowledgment

The authors acknowledge helpful discussions with Prof. Beth Opila.

Appendix A: CFD Analysis of Water Vapor Jet

A preliminary axisymmetric CFD analysis (using commercial software, ANSYS FLUENT (ANSYS Inc., Canonsburg, PA)) was used to investigate several characteristics of the water vapor jet under typical experimental conditions described in Section III (2), namely, whether the pressure at the exit of the capillary is significantly higher than ambient pressure and whether the composition of the jet changed significantly due to radial diffusion of water out of the jet and argon into the jet. The jet in the analysis was created by feeding water vapor into one end of a capillary (1 mm diameter, 150 mm length) at constant mass flow rate ($m = 0.03$ g/s) and uniform velocity (300 m/s), corresponding to gas temperature of 1500°C. The jet exited the other end of the capillary into surrounding static argon gas at pressure of 1 atm and temperature 1500°C. Although in the experiments the surrounding gas was moving, the velocity (0.1 m/s) was negligible compared with the jet velocity and the assumption of static surrounding gas is accurate. The analysis did not account for the presence of the test specimen. Nor did it account for the fact that the water vapor temperature and hence velocity increases continuously between the location of injection (vaporization) and the exit. Therefore, the analysis was not used to assess velocity distributions (radial or axial), which would be expected to be sensitive to this temperature variation.

The pressure at the exit of the capillary is 1.002 atm; and is thus close to the ambient pressure, as assumed in using Eq. (5) to calculate the average jet velocity, $v_{av}$. The analysis also confirms that the gas composition at the center of the jet remains pure argon (i.e., mixing and diffusion of argon into the center of the jet is negligible), at least within 5 mm of the capillary exit, as might be intuitively expected.

Appendix B: Diffusion Equations and Boundary Layer Thickness

Along the line $x_1$ in Fig. 1(c), where the flow is laminar, the steady-state recession rate in the transport-limited regime can be calculated following the analysis of Opila, which begins with a dimensionless correlation function for the Sherwood number, $Sh$, in terms of the Reynolds number, $Re$, and Schmidt number, $Sc$:

$$Sh = \frac{k_1 L}{\rho_v D} = 0.664Re^{1/2}Sc^{1/3}$$

(B-1)

which, with $Re$ given by Eq. (8) and $Sc = \eta/\rho v D$, becomes

$$k_1 = 0.664 \left( \frac{L \rho_B}{\eta} \right)^{1/2} \left( \frac{\eta}{\rho v D} \right)^{1/3} \frac{D \rho_B}{L}$$

(B-2)

where $k_1$ is the average mass flux, $v$ is the gas velocity, $\rho_v$ the equilibrium concentration of the volatile species (Si(OH)$_4$), $\rho_B$ the density of the boundary layer gas (H$_2$O), $D$ the diffusion coefficient of the volatile species in the boundary layer, $\eta$ the gas viscosity, and $L$ is a characteristic specimen length, equal to $x_1$ for the wedge-shaped specimen here. Equation (B-2) can be written in the form of Eqs (10) and (13) with the following substitutions:

$$J_l = k_1 \frac{\rho_{SiO_2}}{MW_{SiO_2}} \frac{MW_{SiC}}{\rho_{SiC}}$$

(B-3)

$$\rho_v = \rho_B \frac{MW_B}{RT}$$

(B-4)

$$\rho_v = \frac{MW_{Si(OH)_4}}{RT} = k \frac{MW_{Si(OH)_4}}{RT} P_{O_2}^3$$

(B-5)

$$k_{eq} \propto \exp \left( \frac{-\Delta H}{RT} \right)$$

(B-6)

$$D = \left[ \frac{0.0018 v_{av}}{\sigma_{vB} \Omega} \right]^{1/2}$$

(B-7)

where the subscripts $B$ and $v$ refer to the boundary layer gas and the volatile species, $P$ is pressure, $\rho$ is density, $MW$ is molecular weight, $k_{eq}$ and $\Delta H$ are the equilibrium constant and enthalpy for reaction (3), $\sigma_{vB}$ is the mean of the collision diameters for the species $v$ and $B$ (i.e., Si(OH)$_4$ and H$_2$O in our case), and $\Omega$ is a dimensionless collision integral. With the temperature dependence introduced through the parameters $\rho_v$, $\rho_B$, and $D$, the exponent in Eq. (13) is $-1/6$. If in addition we account for the temperature dependence of viscosity, given approximately by $\eta \propto T^{3/2}$, the exponent becomes $n \approx -1/4$.

The thickness of the diffusion boundary layer may be evaluated by substituting the expressions above into Eq. (9). The boundary layer thickness increases with increasing $x$, increasing $T$ and decreasing $v$. Therefore, the largest thickness in the current experiments will occur for the higher temperature/lower velocity condition ($T = 1350°C$, $v = 160$ m/s). The parameters needed to estimate the diffusion coefficient are $MW_v = 96$ g/mol (Si(OH)$_4$), $MW_B = 18$ g/mol (H$_2$O), $\rho_{SiC} \approx 3$ A, $\rho_B = 0.0013$ g/cc, and $x_1 = 4$ mm, so we get $Re \approx 1500$, $Sc \approx 1.2$, and maximum thickness $\delta \approx 0.15$ mm.

References


