Theoretical Effects of Vitiated Air Contamination on Ground Testing of Hypersonic Airbreathing Engines

Raymond B. Edelman* and Louis J. Spadaccini†
General Applied Science Laboratories Inc., Westbury, N.Y.

This paper presents the results of an analytical study of the effects of vitiation heating, beginning with air and makeup O_2 at 4000°R, to achieve higher temperatures for ground testing of air-breathing engines. The phenomena investigated include equilibrium, vibrational and chemical relaxation, finite-rate condensation, combustion, mixing, and over-all test engine performance. In general, it has been found that hydrogen and propane-vitiated air may be used to duplicate flight Mach number, pressure, and temperature for altitudes and velocities in the Mach 7–10 flight regime; however, both the equilibrium and finite-rate thrust level obtained for a scramjet engine tested in H_2-vitiated air are lower than the corresponding clean air value. In addition, the presence of free radicals and active species such as OH, O, and H accelerate the combustion process in the test engine, while H_2O and CO_2 can either increase or decrease the reaction time.

Nomenclature

A = area
A_F, A_r = Arrhenius frequency factor
E_F, E_r = activation energy
f = fuel/air ratio, droplet growth rate (dr/dt)
g = acceleration of gravity
h = enthalpy
J = nucleation rate; lb of drops of critical size formed/unit vol/sec
k = Boltzmann constant, reaction rate constant
M = Mach number
m_L = mass of one molecule of condensed phase
n^* = number of molecules in a drop of critical size
P = pressure
$\bar{r}, r^*$ = average and critical drop radii, respectively
R^* = radius of nozzle throat
R = universal gas constant
T = temperature
T_i = internal thrust
V = velocity
x_f = mass fraction of fuel
z = altitude
α = condensation accommodation coefficient: fraction of impinging molecules which stick
α_i = species mass fraction
γ = specific heat ratio
θ_c = cone angle
μ = molecular weight
ρ = density
σ = shock angle
τ = surface tension
Γ = gasification factor
φ = saturation ratio, P_L/P_∞

Subscripts

f = forward reaction
L = condensed phase
0 = freestream conditions
r = reverse reaction
t = stagnation conditions
v = vapor
1–6 = stations shown in Fig. 4

Introduction

The simulation of true flight conditions in testing of hypersonic air-breathing engines requires the significant extension of existing facilities capabilities and operating ranges. One technique frequently suggested to extend the range of existing and proposed facilities is that of vitiation heating, wherein air is preheated in a stagnation chamber by preliminary combustion. Makeup oxygen is added to provide vitiated air with the correct proportion of O_2 (23% by weight). However, such vitiation effects the flow through changes in specific heat ratio and molecular weight, heating and cooling due to dissociation/recombination kinetics and condensation kinetics, and energy distribution due to vibrational relaxation kinetics. The inviscid and viscous flows are both affected since wall boundary-layer structure and fuel jet mixing depend upon Reynolds number and local flow properties bounding these viscous dominated regions.

In a previous paper[1] by the authors, a detailed discussion of the analytical techniques used to describe the foregoing phenomena were presented. The objectives of this work are to define and to evaluate the effects of vitiated air species contamination on combustion research and engine development tests in the Mach 7–10 flight regime. In all cases it is assumed that air with the proper amount of makeup O_2 is passed through a pebble bed heater at 4000°R and then allowed to react with fuel (hydrogen or propane) at 520°R.

Facility Flow

Equilibrium Studies

Figures 1 and 2 show P/P_t, T, γ, M, and molecular weight as functions of the degree of vitiation (x_f = mass fraction of fuel) for two total pressures, with the expansion ratio A/A^* as a parameter. These curves indicate the potential degree of mismatch in flow parameters between pure air and various degrees of vitiated air.

Since large amounts of water vapor are present in the vitiated air, particular attention was paid to the possibility of condensation. Experiments have shown that condensation often does not occur until the isentropic expansion has passed well into the supersaturated region.[2] A kinetic analysis of nozzle condensation[1] indicated that it is often

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Presented as Paper 69-456 at the AIAA 5th Propulsion Joint Specialist Conference, U.S. Air Force Academy, Colo., June 9–13, 1969; submitted June 28, 1969; revision received September 26, 1969. This work was performed for the Arnold Engineering and Development Center under Contract AF F40600-67-0-0007 with technical monitoring by L. Marshall. Reproduction to satisfy the needs of the government is authorized.

* Manager, Thermochemistry and Viscous Flow Section. Member AIAA.

† Senior Scientist. Member AIAA.

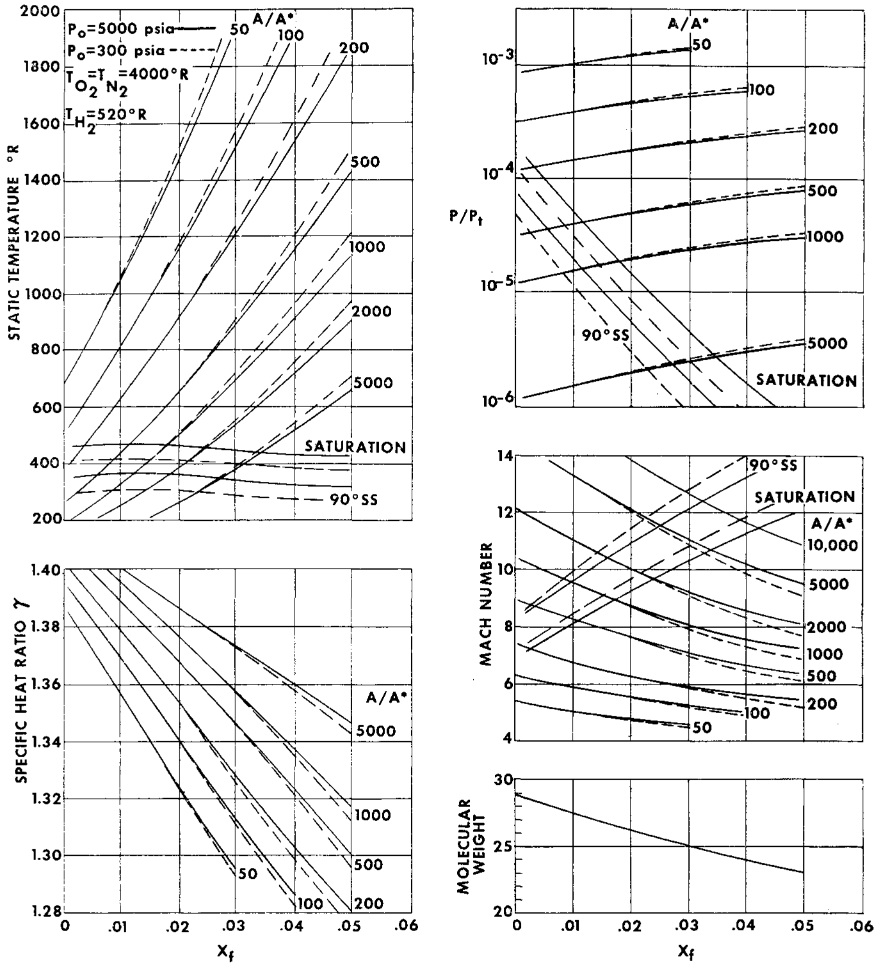

Fig. 1 Test section flow properties for hydrogen-vitiated air.

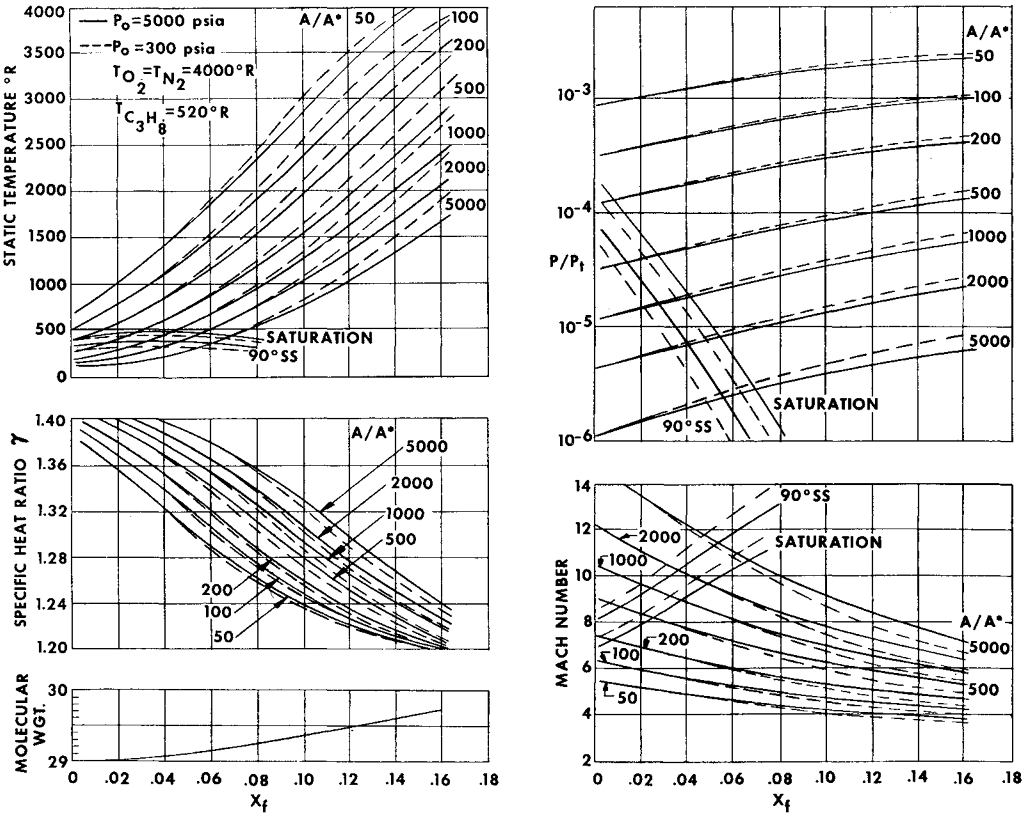

Fig. 2 Test section flow properties for propane-vitiated air.

Table 1 **Tunnel operating conditions required to obtain *T*, *P*, and *M* in hydrogen and propane combustion tunnels**

Flight conditions							Values from H_2 tunnel charts						Values from C_3H_8 tunnel charts					
Alt, kft	T, °R	P, lb/ft²	V, fps	M	P_t, psia	T_t, °R	A/A^*	$x_f \times 10^4$	V, fps	γ	P_t, psia	T_t, °R	A/A^*	$x_f \times 10^4$	V, fps	γ	P_t, psia	T_t, °R
80	397.7	58.5	7,500	7.67	4,100	4,350	250	22	7,500	1.400	4,280	4,250	250	83	7,600	1.397	4,670	4,420
100	408.6	23.3	7,000	7.06	1,000	4,000	170	0	7,000	1.401	1,000	4,000	170	0	7,100	1.401	1,000	4,000
			8,000	8.07	2,400	4,800	390	66	8,080	1.393	3,060	4,700	390	150	8,000	1.394	2,940	4,750
			9,000	9.08	6,000	5,700	915	138	9,250	1.387	8,650	5,280	930	311	8,870	1.388	8,863	5,450
120	433.6	9.6	7,000	6.86	380	4,000	150	0	7,000	1.400	380	4,000	130	0	7,050	1.398	380	4,000
			8,000	7.84	1,000	4,800	340	69	8,200	1.391	1,010	4,700	330	145	7,950	1.393	990	4,700
			9,000	8.82	2,100	5,750	825	143	9,300	1.386	2,980	5,300	825	315	8,900	1.386	2,980	5,400
			9,700	9.50	5,000	6,500	1,600	211	10,100	1.377	6,670	5,740	1,695	468	9,660	1.380	7,250	5,900
140	463.9	4.2	8,000	7.58	330	4,850	270	62	8,100	1.391	325	4,630	310	181	8,120	1.388	390	4,900
			9,000	8.52	700	5,750	725	150	9,600	1.384	1,040	5,250	720	327	8,920	1.383	1,090	5,350
			10,000	9.47	2,000	5,700	1,850	243	10,400	1.373	3,140	5,850	1,900	515	9,880	1.376	3,420	6,000

possible to operate safely in the region bounded by the saturation and 90° supersaturation (SS) lines. Therefore, these lines have been superimposed on the generalized curves of test section flow conditions. The likelihood of condensation increases rapidly beyond the 90° SS curves and individual detailed kinetic calculations are required.

Duplication of Flight Conditions

Table 1 presents typical calculated results for the matching of flight Mach number, static pressure, and static temperature by adjusting A/A^* and x_f to values determined from Fig. 1 or Fig. 2. These calculations, based on equilibrium expansion, show that:

1) The mass fraction of propane required to match flight conditions is between 2.0 and 3.8 times the mass fraction of hydrogen necessary (Table 1). However, the mismatches in molecular weight and the amount of water formed are smaller for propane-vitiated air.

2) When P, T, and M are matched, the mismatches in V are larger for H_2-vitiated air than for propane-vitiated air (e.g., 4–7% higher vs approximately 1% lower for flight velocities of 9000–10,000 fps at 140,000 ft.).

3) The mismatches in stagnation conditions become quite large for both fuels at the higher velocities and altitudes (50–70% higher in P_t and 10–14% lower in T_t). Thus, it is possible to duplicate M, P, and T, at the expense of mismatching P_t and T_t, for altitudes and velocities of interest.

Nonequilibrium Studies

In most wind-tunnel facilities the dwell time of the flow between the heater and the nozzle throat is large enough so that the gas comes to equilibrium before reaching the throat. Beyond the throat, nonequilibrium chemical kinetics and the rate of readjustment of vibrational energy from one distribution to another may become important. A detailed analysis of the effects of finite-rate chemistry and vibrational relaxation indicated that for 10°- and 20°-included-angle conical nozzles, the flow in the facility nozzle remains in chemical and vibrational equilibrium throughout the range of tunnel conditions of interest, and the presence of water vapor reduces the vibrational relaxation time for N_2 and O_2 by up to two orders of magnitude.

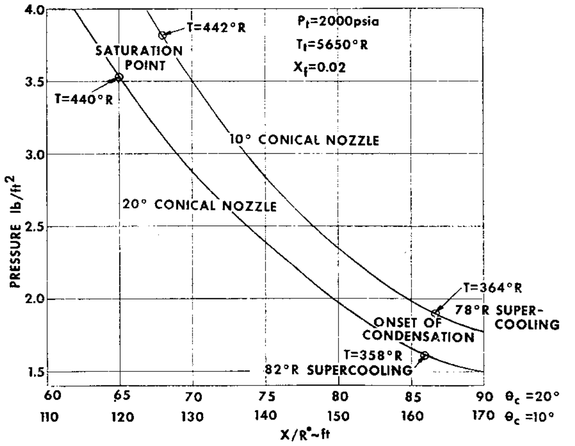

Fig. 3 Prediction of supercooling for homogeneous nucleation.

The equilibrium condensation limits shown in Figs. 1 and 2 indicate that condensation should be considered for many test conditions of interest. However, condensation, like vibrational and chemical relaxation, takes place at a finite rate and depends on the initial conditions including the initial water vapor concentration. If condensation is retarded significantly, the operating range of the tunnel can possibly be extended (depending upon the particular test). On the other hand, if condensation takes place in either the facility nozzle or the test item, the heat released can result in a substantial mismatch in P, T, and α_{O_2} in the gas. In Ref. 1 an analytical model was developed based on classical nucleation rate concepts including the effect of heterogeneous nucleation. It was found that the best agreement with experimental data was obtained by combining the nucleation model of Yang[3]

$$J = Pv^2 \exp B/\rho_L T^2 \tag{1}$$

where

$$B = \tfrac{1}{2}\ln(2\tau m_L/\pi) - 2\ln k + \ln\Gamma - 2\ln\varphi[n^*/4 - (n^*/2)^{1/3} + 1]$$

$$n^* = (4\pi\rho_L/3m_L)r^{*3}$$

$$r^* = 2\tau\mu_L/\rho_L RT \ln\phi$$

with the growth law given by Hill[4]

$$f = \frac{\alpha}{\rho_L V}\left[P_v - P_0 \exp\left(\frac{2\tau\mu_v}{\rho_L RT\bar{r}}\right)\right]\left(\frac{m_L}{2\pi kT}\right)^{1/2} \tag{2}$$

This study showed that the critical "onset" point and the "downstream" properties could be predicted with a reasonable degree of confidence.

The results in Fig. 3 indicate that a 70–80°R supercooling is possible for homogeneous nucleation in H_2-vitiated tunnels. This result is in fair agreement with the empirical value of 90°R supercooling originally assumed in connection with the previous discussions on equilibrium processes. In the case of vitiation with propane, for comparable conditions of pressure and temperature in the supply chamber, a smaller amount of water vapor will be present and a lower condensation temperature and at least as much or more supercooling can be tolerated (see Ref. 2).

Test Engine Analysis

Equilibrium Performance

A one-dimensional analysis has been carried out to determine the effects of vitiation on scramjet engine performance. Calculations were made for pure and hydrogen-vitiated air using the GASL IBM 7094 machine program,[5] which calcu-

Table 2 One-dimensional equilibrium chemistry performance program results: effects of hydrogen vitiation

	Station 0		Station 3		Fuel properties		Station 4		Station 6	
	Dry air	Vitiated air	Dry air	Vitiated air	Dry air	Vitiated air	Dry air	Vitiated air	Dry air	Vitiated air
u, fps	9,881.45	10,359.6	8,758.4	9,256	7,588.3	7,588.3	8,742.2	9,208.4	11,949	12,299
M	9.50	9.50	4.034	4.275	1.002	1.002	2.66	2.79	5.357	5.43
P, psia	0.0182	0.0182	2.93	2.63	2.93	2.63	2.93	2.63	0.0182	0.0182
T, °R	448	448	2,056.8	1,864.5	1,671.4	1,671.4	4,511	4,205	1,883	1,788
P_t, psia	1,320	2,000	750	1,128	5.55	4.97	...	...	...	...
T_t, °R	6,454.6	5,803.85	6,396.1	5,749.2	2,000	2,000	...	...	...	...
μ, g/mole	28.85	25.82	28.85	25.82	2.016	2.016	23.76	21.85	24.55	22.36
ρ, slug/ft³	3.40×10^{-6}	3.043×10^{-6}	1.19×10^{-4}	1.05×10^{-4}	...	...	4.47×10^{-5}	3.96×10^{-5}	6.88×10^{-7}	6.6×10^{-7}
γ	1.402	1.38	1.33	1.305	...	...	1.139	1.14	1.305	1.289
A/A_0	1.0	1.0	0.0322	0.0322	...	...	0.0886	0.0888	4.2	4.0
Mass fractions					Mixture station 3					
O_2	0.232	0.2335	0.232	0.2334	0.2253	0.2268	0.0157	0.01524	7.84×10^{-5}	$2.57 \times 10^{-}$
H_2O	0	0.2055	0	0.2055	0	0.1997	0.2152	0.4225	0.2537	0.455
N_2	0.768	0.561	0.768	0.561	0.746	0.545	0.743	0.543	0.7462	0.545
H_2	0	0	0	3.0×10^{-11}	0.02839	0.02857	0.00305	0.002658	3.3×10^{-8}	2.37×10^{-8}
H	0	0	0	1.05×10^{-14}	0	1.02×10^{-14}	4.59×10^{-4}	2.17×10^{-5}	0	0
O	0	0	3.4×10^{-9}	2.86×10^{-10}	3.9×10^{-9}	2.8×10^{-10}	0.0024	0.00106	0	0
OH	0	0	0	4.1×10^{-7}	0	3.99×10^{-7}	0.0134	0.01107	2.6×10^{-7}	1.0×10^{-7}
NO	0	0	1.5×10^{-4}	4.9×10^{-5}	1.48×10^{-4}	4.79×10^{-5}	0.0067	0.0041	1.15×10^{-6}	3.26×10^{-7}
Pressure recov.	...	...	0.57	0.57	...	...	...	...	...	...
C_T	...	...	...	...	...	...	...	...	0.54	0.49
I_f, sec	...	...	...	...	...	...	...	...	2,837	2,692
Thrust/A_0P_0	...	...	...	...	...	...	...	...	34.15	30.6

lates internal flow conditions with the assumption of chemical equilibrium. Figure 4 shows the engine stations considered. The calculations performed are based on $M_0 = 9.50$ and $P_t = 2000$ psia with $x_f = 0.023$ and the tunnel state at the equilibrium saturation point. The flow conditions for dry air and H_2-vitiated air are compared at each engine station in Table 2. Freestream, T, P, and M were the same in both cases, as were inlet geometry and pressure recovery. Differences in V, T_t, and P_t resulted from the vitiation. The hydrogen fuel for the engine was added in both cases at a total temperature of 2000°R, equivalence ratio of 1.0, and fuel expansion pressure ratio of 1.89. Constant pressure burning was assumed. The results indicate that M is higher and T is lower throughout the engine in the vitiated case.

The dashed curves in Fig. 5 compare internal thrusts for dry and vitiated air for a range of engine nozzle-to-freestream area ratios. The internal thrust parameter is defined as

$$\frac{T_i}{P_0 A_0} = \left(\frac{V\mu}{gRT}\right)_0 [(1+f)V_6 - V_0] + \frac{P_6}{P_0}\frac{A_6}{A_0} - 1 \quad (3)$$

The dashed curves in Figure 5 show that the equilibrium-reaction internal thrust obtained for hydrogen-vitiated air is about 10% lower than that obtained for dry air. This difference is due to the larger amount of water vapor in the vitiated air, which lowers the molecular weight and hence the mass flow captured. In addition, the temperature rise due to combustion is lower for vitiated air because it has the higher specific heat. These effects combine to produce a net decrease in thrust for vitiated air.

Nonequilibrium Analyses

In analyzing the nonequilibrium flow in the test engine, vibrational relaxation, finite rate combustion, and nozzle recombination effects were considered.

Inlet

The effect of vibrational nonequilibrium on oblique shocks typical of those encountered in a high-speed inlet flow were estimated using the two limiting cases: vibrational energy frozen at a preshock level determined by the preshock translational temperature, or vibrational energy equilibrated to the postshock translational temperature. Of course, the relaxation of temperature due to finite-rate chemical processes is quite important behind a shock, and may be strongly coupled to the vibrational energy relaxation process. Usually chemical relaxation requires a longer time than vibrational relaxation.

The effects of vibrational relaxation on test inlet oblique shock strength and downstream properties were investigated for hydrogen-vitiated air at $P_t = 2000$ psia, $x_f = 0.02$, and $z = 145{,}000$ ft. An inlet wedge angle of 10° was assumed, and both frozen and equilibrium chemistry were considered. As a comparison, calculations were made for a pure air system at equivalent conditions. The results are summarized in Table 3. For the cases considered, the differences in shock angles and postshock velocities are small. For pure air, the postshock pressure is ~3% higher and the postshock temperatures are 10% higher than the corresponding cases in vitiated air. The assumption of either frozen or equilibrium chemistry gives essentially the same result for the composition (differences in α_{O_2} and α_{N_2} across the shock are negligible) but minor differences in temperature and pressure occur.

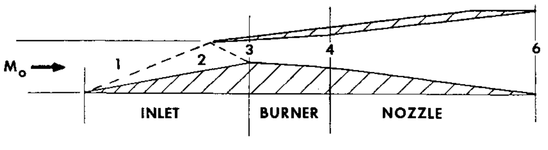

Fig. 4 Scramjet analytical model.

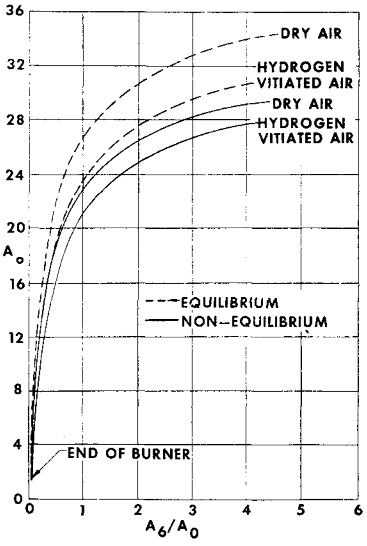

Fig. 5 Engine performance for dry and hydrogen-vitiated air.

Table 3 Results of inlet shock calculations for clean air and H_2-vitiated air; $P_1 = 0.0247$ psia, $V_1 = 9998$ fps, turning angle = 10°, $\alpha_{O_2} = 0.232$

Shock Model		H_2-vitiated air $P_t = 2000$ psia, $x_f = 0.02$, $T_1 = 442°R$, $\alpha_{N_2} = 0.589$, $\alpha_{H_2O} = 0.179$				Clean air $T_1 = 471.5°R$, alt = 145 kft, $\alpha_{N_2} = 0.768$			
Chem.	Vib.	σ, deg	P_2, psia × 10^4	T_2, °R	V_2, fps	σ, deg	P_2, psia × 10^4	T_2, °R	V_2, fps
Froz.	Equil.	14.52	1516	848.2	9710	14.57	1564	938.7	9709
Froz.	Froz.	14.54	1517	851.4	9710	14.58	1568	945.9	9708
Equil.	Equil.	14.49	1514	843.3	9711	14.52	1560	929.7	9710

Table 4 Chemical kinetic reaction mechanism[6]

Reaction No.	Reaction	A_f	E_f	A_r	E_r	Ref.
1	$O + H_2 = OH + H$	3.3×10^{12}	7.14	1.4×10^{12}	5.19	7–10
2	$H + O_2 = OH + O$	2.4×10^{14}	16.75	$3.2 \times 10^{11}T^{0.47}$	0.10	10
3	$OH + H_2 = H + H_2O$	6.3×10^{13}	5.9	2.4×10^{14}	20.69	10
4	$OH + OH = H_2O + O$	7.6×10^{12}	1.0	6.9×10^{13}	17.74	10
5	$H + H + M = H_2 + M$	$2 \times 10^{18}T^{-1}$	0	$2.4 \times 10^{19}T^{-0.86}$	103.24	10
6	$H + OH + M = H_2O + M$	$2.3 \times 10^{21}T^{-1.5}$	0	$1.2 \times 10^{23}T^{-1.34}$	118.027	10
7	$O + H + M = OH + M$	3×10^{14}	0	$7.5 \times 10^{14}T^{0.06}$	101.29	10
8	$O + O + M = O_2 + M$	2.2×10^{13}	0	$2.5 \times 10^{16}T^{-0.5}$	117.9	11, 12
9	$CO + OH = CO_2 + H$	3.2×10^{12}	6.3	$2.7 \times 10^{17}T^{-0.79}$	30.7	13–16

The results can be interpreted as follows. Allowing all reactions to go to equilibrium yields a lower temperature, since endothermic dissociation removes energy from the translational mode (temperature) and stores it in internal energy. Assuming frozen vibrational energy means that more energy is available for translational and rotational modes, since the quantity $h + V^2/2$ must be constant across the shock. This extra available energy results in a higher temperature since the velocity remains essentially unchanged.

Combustor

Since vitiation has only a small effect upon pure mixing,[1] the emphasis here will be focused on the effects of vitiation on ignition delay and reaction times. It was determined that 18 elementary chemical reactions involving nine species are important in the combustion process applicable to the study of hydrogen-fueled combustors supplied by pure air, hydrogen-vitiated air, or hydrocarbon-vitiated air. These reactions are listed in Table 4 together with selected forward and reverse rate constants. The rate constant is expressed in the usual form

$$k_f = A_f \exp(E_f/RT) \tag{4}$$

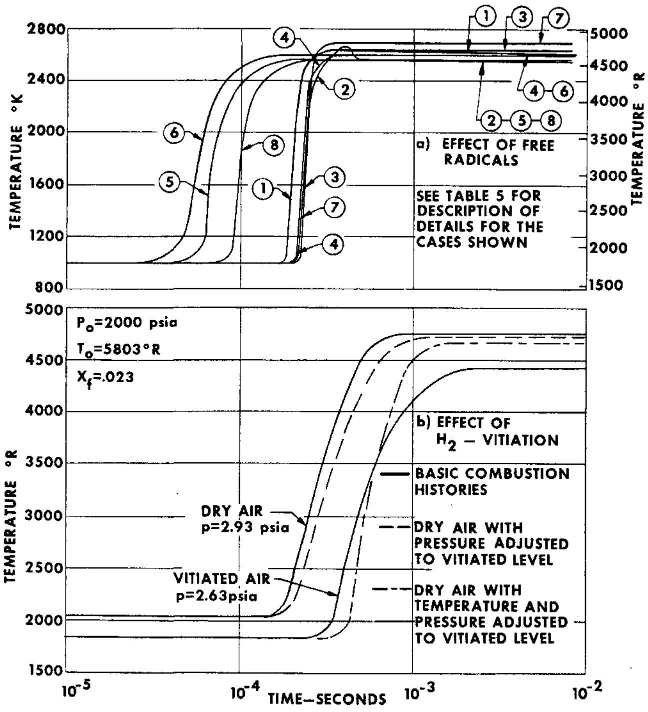

Fig. 6 Effects of initial free radical concentration and vitiation on H_2-Air combustion histories.

Table 5 gives a range of contamination levels that have been investigated for a hydrogen-fueled combustor under test in either hydrogen- or propane-vitiated tunnels. The results shown in Fig. 6a indicate that the addition of 10^{-5} mass fraction of OH reduces the ignition delay by a full order of magnitude [cases 5 and 6 vs case 7 (pure air)]. Water and CO_2 act as inert diluents (in cases 5 and 6) and tend to increase ignition and reaction time and decrease the combustion temperature in proportion to their effect upon the heat capacity of the mixture. In particular, water has a specific heat about twice that of pure air and accounts for the slightly longer delay time for case 5 in comparison to case 6. However, if small amounts of either H_2O or CO_2 are present in a mixture with no initial concentration of free radicals (cases 1 and 4) they tend to speed up the reaction process by producing an abundance of free radicals early in the combustion history, and at a rate proportional to the local P and T. This results in a reduction in combustion time in comparison with pure air (case 7). Thus, it is evident that combustion is controlled by the initial concentration of

Table 5 Cases chosen for the study of the effect of vitiation on finite-rate stoichiometric combustion of hydrogen at 1000°K and 1 atm

	Air station 3 $\alpha_{O_2} = 0.232$				Mixture station 3 $\alpha_{O_2} = 0.2254$, $\alpha_{H_2} = 0.02837$			
Case	α_{N_2} × 10^3	α_{H_2O} × 10	α_{CO_2} × 10	α_{OH} × 10^7	α_{N_2} × 10^4	α_{H_2O} × 10^4	α_{CO_2} × 10^4	α_{OH} × 10^7
1	668	1	0	0	6490	972	0	0
2	568	2	0	0	5519	1944	0	0
3	668	0	1	0	6490	0	972	0
4	568	0	2	0	5519	0	1944	0
5	568	2	0	100	5519	1944	0	100
6	568	0	2	100	5519	0	1944	100
7	768	0	0	0	7462	0	0	0
8	568	2	0	1	5519	1944	0	1

free radicals, or the subsequent ability for the mixture to generate them.

Of particular interest is the effect of vitiation upon combustion studies under real test conditions. The initial state entering the combustor process is given in Table 2 at station 3. The results which are presented in Fig. 6b indicate that the ignition delay and reaction times for the dry air are shorter than those obtained for vitiated air. This result is not in contradiction with previous discussions on the effects of free radicals in reducing combustion time but rather shows the effect of the mismatch in initial combustor state when only the freestream M, P, and T are matched. To illustrate this point, the combustion histories were regenerated showing a comparison on the basis of equal combustor inlet static pressures and temperatures. Adjusting the dry air temperature and pressure results in a somewhat longer delay time compared with the vitiated case. Thus, it is important to distinguish between these essential differences particularly in coupled inlet/combustor testing.

Nozzle

In order to evaluate the nonequilibrium effects due to species recombination in the engine nozzle, a finite-rate expansion from the burner exit (station 4 of Fig. 4) was carried out for the case shown in Table 2 using the mechanism in Table 4. The engine nozzle was assumed to be conical with a 7.5° half-angle. The results for dry and hydrogen-vitiated air are shown by the solid curves in Fig. 5. In addition to a reduction in the level of thrust obtained for both dry and vitiated air, the results indicate that the nonequilibrium effects also tend to reduce the percentage difference between cases. That is, for a finite-rate expansion, the internal thrust obtained for vitiated air is about 5.3% lower than that obtained for dry air. This, when compared with $\sim$10% difference obtained for chemical equilibrium (dashed curves), draws attention to the fact that the level of dissociation for dry air is greater than that of vitiated air due to its higher temperature. Thus, its departure from equilibrium is also expected to be greater. In addition, comparing the nonequilibrium results with the equilibrium results, it is observed that over-all test engine thrust losses of up to 16.5% are obtained for dry air, while for the corresponding hydrogen vitiated air tests, losses up to 13% are obtained in comparison to their equilibrium values.

Conclusions

The following conclusions are drawn from this examination of a limited number of points in the Mach 7–10 flight regime.

1) Vitiation with propane in comparison to hydrogen results in substantially smaller mismatch in molecular weight while also extending the condensation limit.

2) Increasing stagnation pressure acts to speed up condensation and reduce the allowable Mach number in the test section.

3) Hydrogen- and propane-vitiated air may be used to duplicate flight Mach number, static pressure and static temperature for altitudes and velocities in the Mach 7–10 flight regime.

4) For 10°- and 20°-included-angle conical nozzles, the flow in the facility nozzle remains in chemical and vibrational equilibrium throughout the range of tunnel conditions of interest.

5) Supercooling of from 70–80°R is predicted for 10°- and 20°-included-angle facility nozzles for tunnels utilizing hydrogen-vitiated air.

6) The equilibrium thrust level obtained for a scramjet engine tested in hydrogen-vitiated air ($P_0 = 2000$ psia, $x_f = 0.023$, $M = 9.5$) is about 10% lower than the corresponding clean air value.

7) Test inlet oblique shock strength and downstream properties are essentially insensitive to either frozen or equilibrium assumptions for the vibrational energy level (this conclusion also applied to chemically frozen or equilibrium assumptions).

8) The presence of free radicals and active species such as OH, O, and H accelerate the combustion process in the test engine. Up to an order of magnitude reduction in delay time is observed with the presence of 10^{-5} mass fraction of OH in the initial flow entering the scramjet combustor.

9) The presence of H_2O and CO_2 in an initially equilibrium scramjet combustor entrance flow can either increase or decrease the ignition delay time. This depends upon the initial temperature, pressure and concentration level, which can either result in a significant generation of free radicals and accelerate combustion or result in an increase in heat sink capability due to H_2O and suppress combustion. The effect in a particular case must be determined for the appropriate inlet state of flow.

10) Nonequilibrium recombination losses in the test engine nozzle are important for both vitiated and clean air flows. In addition, over-all test engine thrust losses of up to 16.5% are observed for dry air, while for the corresponding hydrogen vitiated air tests, losses up to 13% are obtained in comparison to their equilibrium values.

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