Effects of Vitiation in NASA Langley Hypersonic Tunnels

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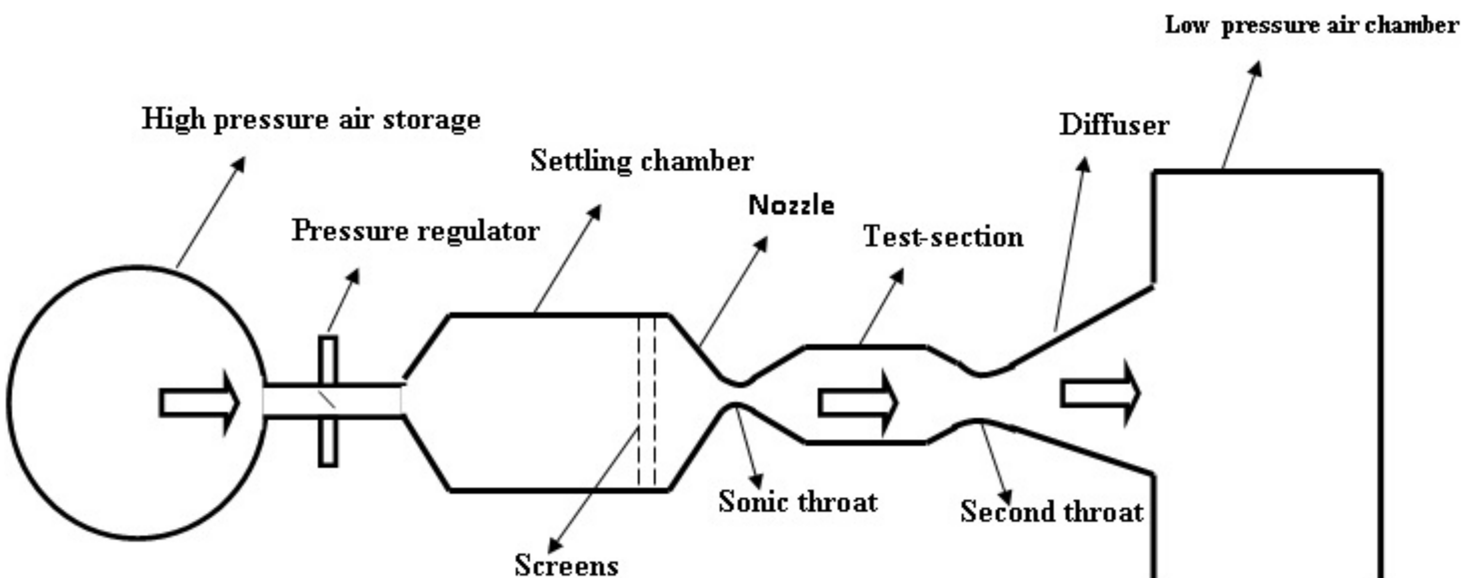
March 2018

Vitiation

- Definition
  - To reduce the value or quality of; impair or spoil
  - To corrupt morally; debase
- Why is vitiation needed in hypersonic tunnels?



Air Heating Methods

- Arc heating or inductive heating
  - Good for high heating (high Mach number) tunnels
  - Low levels of vitiates (NO and electrode material)
  - Expensive
- Preheated pebble bed or radiant heating
  - Very low vitiate level in test medium
  - Limited heating range
  - Transient
- Combustion heated
  - Combustion products change composition of air
  - Test conditions altered
  - But cheap to build and operate
  - Equivalent to a 200MW arc heater in amount of energy transferred to test medium

Vitiates in Tunnel Flow

- Molar composition of typical vitiates in tunnel flows

	Clean Air	Arc Heater	H2 + Air	CH4 + Air
H_2O	<< 1	0.1	5 - 33	3 - 21
CO_2	0.03	0.03	0.03	1.4 - 10
CO	0	0	0	< 0.2
NO	< 0.01	0.2 – 3.5	< 1.4	< 1.6
Other		Cu		

From "Air Vitiation Effects on Scramjet Combustion Tests", G. L. Pellet et al. AIAA-2002-3880

Example of Vitiate Composition

- Combustion heating in the 8-foot HTT achieved by the burning of natural gas and oxygen
- Mach 5 run conditions

	Clean Air	Vitiated Air
O2	0.20950	0.21120
N2	0.78088	0.63816
CO2	0.00030	0.04767
H2O		0.09533
Ar	0.00932	0.00764
Mol. weight	28.964	28.756

Issues With Combustion Heating

- Composition of the tunnel gas not the same as air
- Oxygen level needs to be adjusted
  - Match molecular or mass concentrations?
- Presence of combustion products in the flow
  - Mean molecular weight not the same as in pure air
  - Heat capacity not the same
  - Effect of products on combustion processes
  - Incomplete heater combustion will affect reactions more
- Condensation of water vapor
  - At certain simulated pressures and temperatures, water can condense out of the flow
  - Process releases heat, reduces total pressure
  - Mach number changes

Specifying Flow Conditions

For Mach 5 test point in 8-foot tunnel

Case	Matched Parameters	Mach # [-]	Velocity [m/s]	T_{static} [K]	T_{total} [K]	P_{static} [Pa]	P_{total} [kPa]	DP [kPa]	H_{total} [kJ/kg]
0	Clean Air	5.000	1455.0	210.5	1192.2	6559.6	3785.2	114.9	1270.
1	M, T_{total}, P_{total}	5.000	1487.6	220.3	1192.2	5916.5	3785.3	102.8	1336.
2	M, T_{total}, P_{static}	5.000	1487.6	220.3	1192.2	6559.6	4196.7	113.9	1336.
3	M, $T_{total,}$ DP	5.000	1487.6	220.3	1192.2	6615.1	4232.2	114.9	1336.
4	M, H_{total}, P_{total}	5.000	1450.3	209.3	1139.2	5997.9	3785.0	104.2	1270.
5	M, H_{total}, P_{static}	5.000	1450.3	209.3	1139.2	6559.6	4139.4	114.0	1270.
6	M, $H_{total,}$ DP	5.000	1450.3	209.3	1139.2	6615.1	4174.5	114.9	1270.
7	M, $T_{static,}$ P_{total}	5.000	1454.3	210.5	1145.0	5989.8	3785.7	104.1	1277.
8	M, T_{static}, P_{static}	5.000	1454.3	210.5	1145.0	6559.6	4145.8	114.0	1277.
9	M, $T_{static,}$ DP	5.000	1454.3	210.5	1145.0	6615.1	4180.9	114.9	1277.
10	V, H_{total}, P_{total}	5.057	1455.0	205.9	1142.0	5601.5	3785.0	99.6	1273.
11	V, H_{total}, P_{static}	5.057	1455.0	205.9	1142.0	6559.6	4432.4	116.6	1273.
12	V, H_{total}, DP	5.057	1455.0	205.9	1142.0	6461.4	4366.1	114.9	1273.

From Cuda and Gaffney, Analysis of the Effects of Vitiates on Surface Heat Flux in Ground Tests of Hypersonic Vehicles. JANNAF

Comparing Fluxes

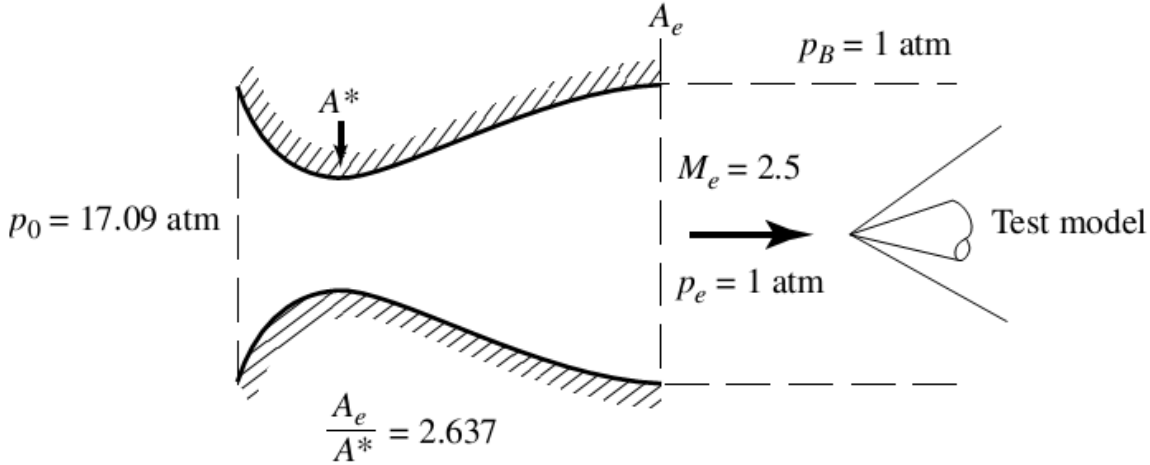
For Mach 5 test point in 8-foot tunnel

Case	Matched Parameters	Clean Air			Vitiate Test Gas			Variance [%]			RMS
		rU	rU^2 + P	rUH	rU	rU^2 + P	rUH	rU	rU^2 + P	rUH	[%]
1	M, T_{total}, P_{total}	157.9	236.4	200.6	138.2	211.4	184.6	–12.52	–10.54	–7.97	18.2
2	M, T_{total}, P_{static}	157.9	236.4	200.6	153.2	234.4	204.7	–3.02	–0.82	2.03	3.73
3	M, T_{total}, DP	157.9	236.4	200.6	154.5	236.4	206.4	–2.20	0.02	2.90	3.64
4	M, H_{total}, P_{total}	157.9	236.4	200.6	143.7	214.4	182.5	–9.00	–9.27	–9.00	15.8
5	M, H_{total}, P_{static}	157.9	236.4	200.6	157.2	234.5	199.6	–0.48	–0.78	–0.48	1.04
6	M, H_{total}, DP	157.9	236.4	200.6	158.5	236.5	201.3	0.36	0.06	0.36	0.51
7	M, T_{static}, P_{total}	157.9	236.4	200.6	143.1	214.1	182.8	–9.38	–9.40	–8.88	16.0
8	M, T_{static}, P_{static}	157.9	236.4	200.6	156.7	234.5	200.2	–0.77	–0.78	–0.21	1.12
9	M, T_{static}, DP	157.9	236.4	200.6	158.1	236.5	201.9	0.08	0.06	0.64	0.65
10	V, H_{total}, P_{total}	157.9	236.4	200.6	136.9	204.7	174.3	–13.34	–13.37	–13.11	23.0
11	V, H_{total}, P_{static}	157.9	236.4	200.6	160.3	239.8	204.1	1.48	1.44	1.75	2.71
12	V, H_{total}, DP	157.9	236.4	200.6	157.9	236.2	201.0	–0.04	–0.08	0.23	0.24

From Cuda and Gaffney, Analysis of the Effects of Vitiates on Surface Heat Flux in Ground Tests of Hypersonic Vehicles. JANNAF

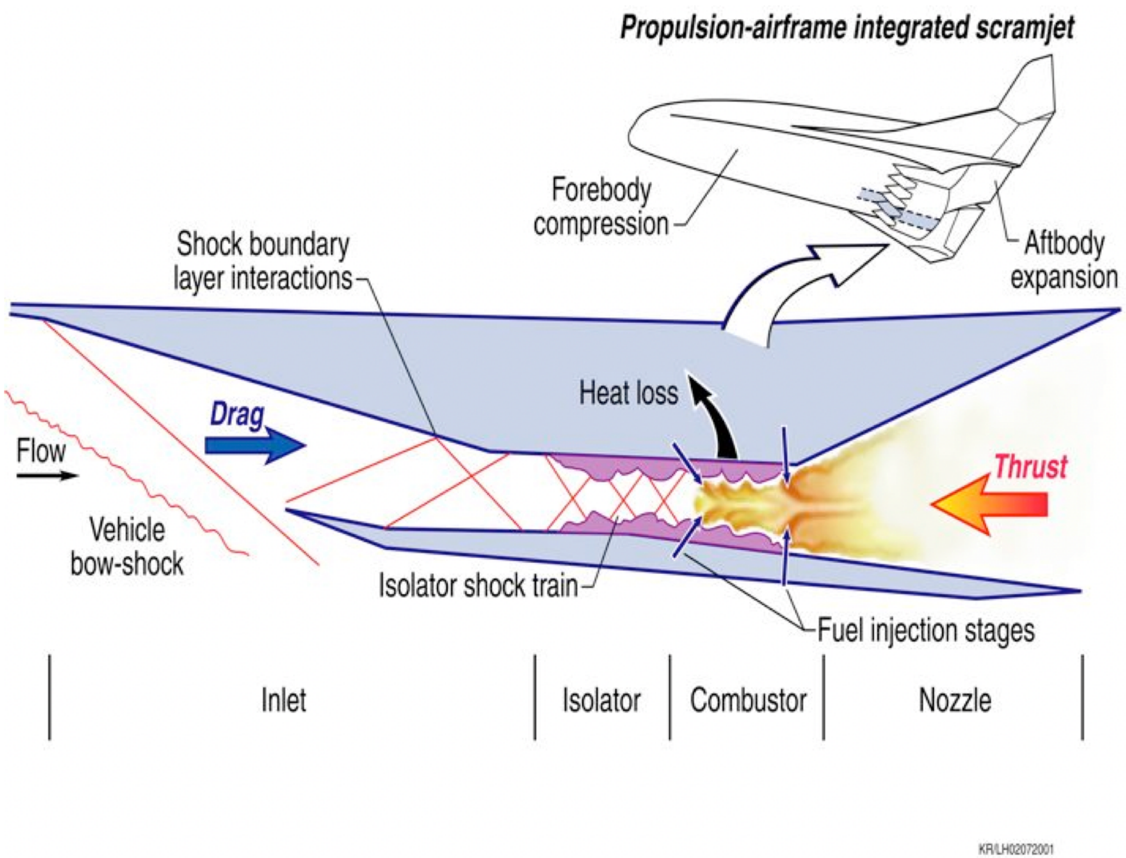
Condensation

- Condensation cause releases heat into flow resulting in increase in total temperature and decrease in total pressure.
  - Speed of sound uncertain
- Strong shock will re-vaporize, but not full recovery of properties
  - Nozzle may not operate as designed and have non-uniform flow
- Issues with static pressure measurements vs pitot



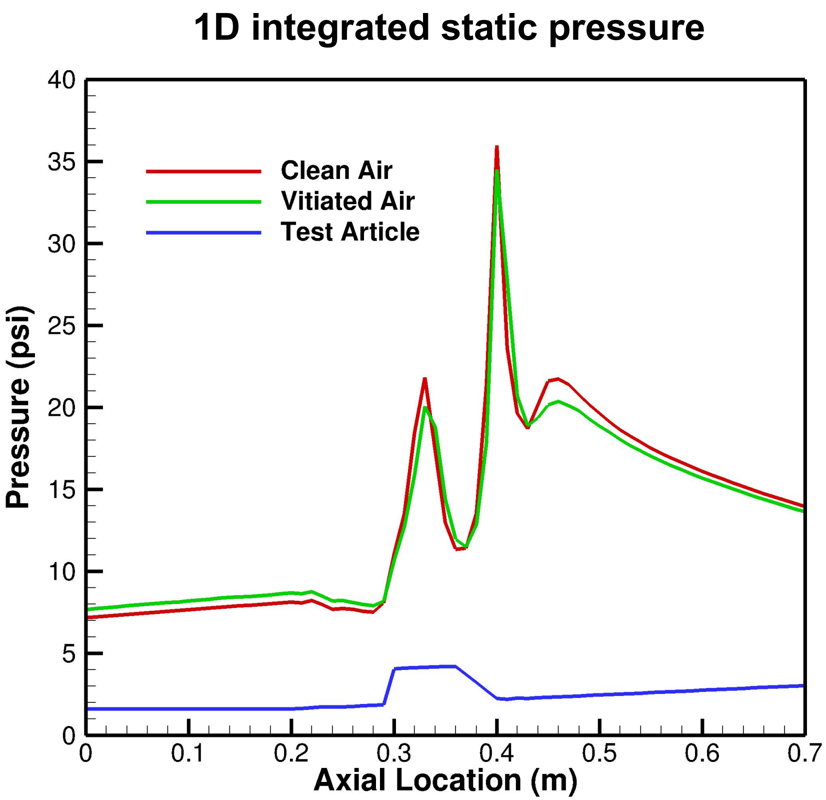
Chemical Kinetics

- Changes in gas composition can affect chemical reactions in both transient and steady modes
  - Incomplete combustion heating changes vitiate composition



Vitiation Example

- HDCR ground test rig used as example (1)
  - Matched flow conditions with Pt, Tt and mass flow
  - Vitiation compositon same as 8-foot HTT at Mach 5
  - 32 species, 208 reaction mechanism used
- Thrust reduced by about 20% due to vitiation.
  - Same trend seen in GASL tests (2)
- Difficult to evaluate ignition delay as considerable uncertainty in kinetics for this phenomena



(1) Norris, Evaluating the Uncertainty in JP-7 Kinetics Models Applied to Scramjets, JANNAF, 2017
(2) Sklar et al. Test Media Effects on the Performance of a Heavy-Weight, Hydrocarbon-Fueled, Direct Connect Rectangular Scramjet Combustor, JANNAF 2011

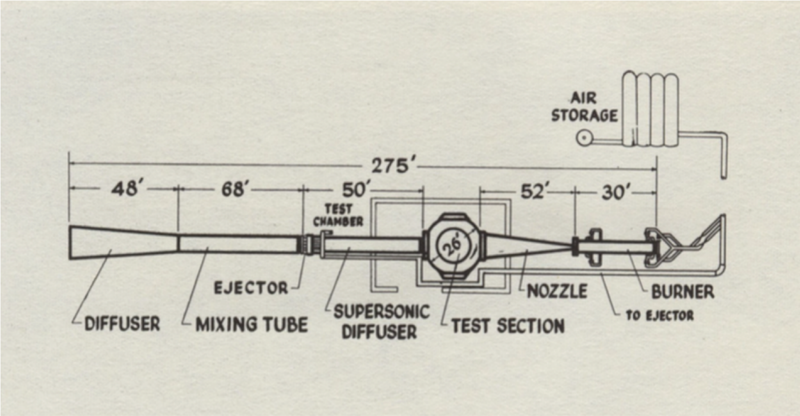
Vitiation Guidelines

- Selection of which variables to match can be test-dependent
  - Potential different variables for surface heating, combustion, aerodynamics
- Condensation can be an issue for testing
  - Flow variability and measurements may be off
- Vitiates can change mass capture, fuel-air ratio, combustion and resulting thrust
  - Very case dependent
- The presence of vitiates in the flow can suppress ignition and combustion due to the greater heat capacity of the flow
  - Less temperature rise, so slower combustion
- The presence of free radicals due to incomplete combustion of the heating fuel can greatly enhance the ignition and combustion process
  - Jump-starts combustion process

Backup Slides

8 Foot High Temperature Tunnel

- Mach 3 - 7
- Nozzle 96 inches diameter
- Altitiude
  - 80 to 120 k-ft
- Test Section
  - 8 ft x 12 ft
- Model weight
  - Up to 40,000 lb
- Test duration
  - 60 seconds
- Combustion vitiated with oxygen added



8 Foot High Temperature Tunnel