AE 5535 Hypersonic Air-Breathing Vehicle Analysis

Assigned: January 22, 2021
Due: February 15, 2021

KEY

Consider the attached representation of a hypersonic air-breathing (scramjet-powered) vehicle (modeled after the X-43 or X-51). The vehicle is 'one meter width', where width is into the paper (i.e., this is analyzed as a '2-D' vehicle). The top figure shows the vehicle configuration and related nomenclature for sizing the vehicle, etc. The bottom sketch provides a view of the vehicle at angle of attack, in flight, with shock-on-lip condition at cowl lip (leading edge of the cowl) and reflected shock cancellation at combustor entrance (2-shock inlet, with contained shocks). For this vehicle, the cowl extends to the exit plane of the nozzle (trailing edge of vehicle) as shown. The combustor (from ci to ce) has constant cross-sectional area.

The vehicle to be analyzed has the following characteristics (referred to the vehicle configuration as shown on following page):

xlinlet = 5 m (inlet length from leading edge of vehicle, i, to combustor entrance, ci)

xlcomb = 0.5 m (combustor length from ci – combustor entrance - to ce – combustor exit)

xlnoz = 3 m (nozzle length from nozzle entrance at ce to exit plane of vehicle at e)

height of engine exit plane (at e) = 1.2903 m

wing setting angle = 5 degrees

total wing planform area = 14.5 m^2

combustor entrance height (Aci) = 0.156 m (also = Ace; constant area heat addition)

top surface angle = 3.50298 degrees

inlet angle = 7 degrees

xlforcowl (length of portion of cowl forward of combustor entrance) = 1.213243 m

Ai (height of captured air streamtube at vehicle leading edge at angle of attack = 4 degrees) = 1.0322 m

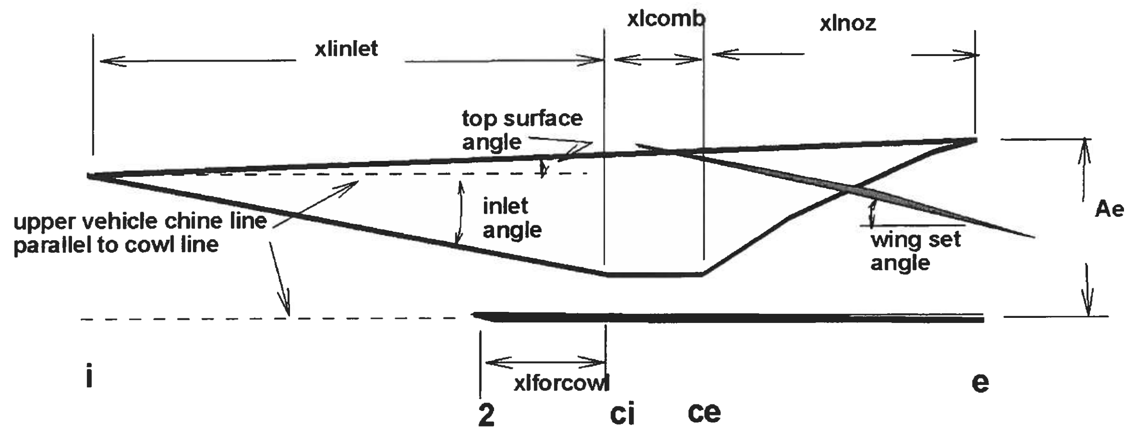
For this vehicle operating at 4 degrees angle of attack with a velocity of 3048.0 m/s at 30 km altitude (use ambient T = 231.24K and ambient P = 1185.5 N/m^2), find 1) the heat rate in the combustor and 2) the vehicle mass (use g = 9.81 m/s^2) ***required for cruise*** at these conditions.

Also provide/tabulate Mach, pressure, temperature, total pressure, total temperature, and velocity magnitude at all relevant stations (i, 2, ci, ce, e) in the propulsive flow path, as well as all give the oblique shock angles and flow conditions behind all shocks and expansions on all relevant vehicle surfaces.

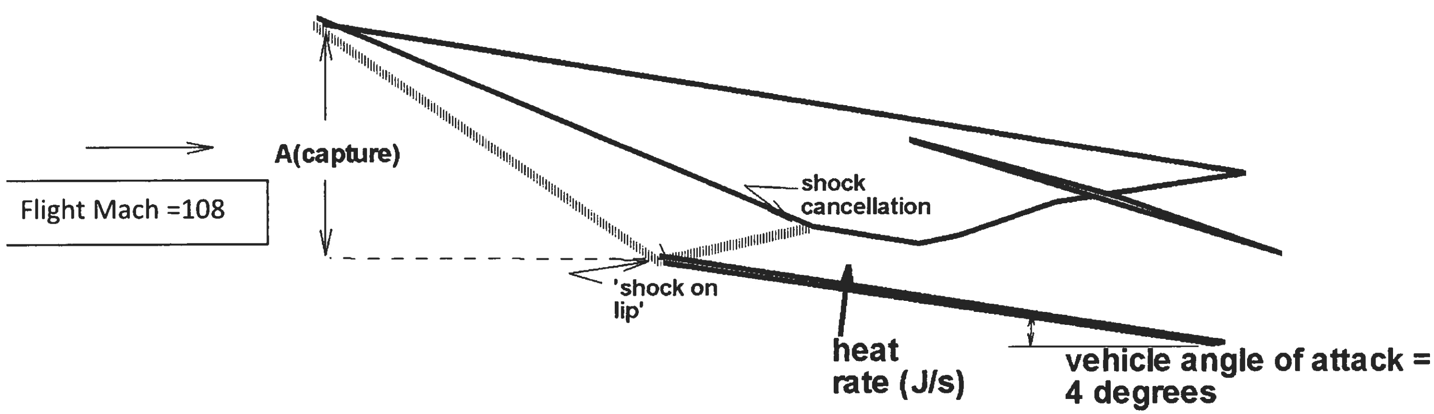
Provide a full and comprehensive break-down of all component forces (inlet, combustor-nozzle, top surface, wing top, wing bottom, cowl bottom) in terms of axial and vertical contributions to the overall axial and vertical aerodynamic forces experienced by the vehicle.

Modeling assumptions: Use constant ratio of specific heats $\gamma = 1.4$, R (gas constant) = 287 J/kg-K, and C_p = 1004.5 J/kg-K everywhere. Assume that ALL wetted surfaces of this vehicle (internal and external) are inviscid (i.e. no friction). Assume isentropic flow in the nozzle (from ce to ci). Use the equations for oblique shocks and Prandtl-Meyer expansion waves (as appropriate) in order to calculate the conditions necessary to do the force analysis; also use equations (**not tables or charts**) to calculate all necessary aspects of engine and airframe flow; all analysis in this project is done using basic compressible flow theory and techniques. Use one-dimensional inviscid heat addition ('Rayleigh') analysis in combustor.

vehicle configuration



vehicle in flight (angle of attack = 4 degrees)



Results Summary (Please fill out and put this in your submission)

M_i (Flight Mach number) = 10

$\dot{Q}$ required to cruise = 9.824×10^7 Watts (if $h = 1.2 \times 10^8$ J/kg → hydrogen → $\dot{m}_f = 0.819$ kg/sec, $f = 0.0146$)

$\dot{m}$ (air flow rate captured by vehicle and processed in engine) = 56.2 kg/sec

Mass of vehicle required for cruise = 12707 kg (Weight = 124656 N)

Aerodynamic forces (summary):

Component	F_x (N)	F_y(N)
Inlet*	7069	15984
$\boxed{\text{Combustor-nozzle (ci to e)}}$	-24130	1687.3
Wing top	-185.6	-1172
Wing bottom	16360	103294
Wing total	16174.5	102122
Bottom of vehicle (cowl bottom)	964.3	13790
Top of vehicle	-77.4	-8927
Overall vehicle (total)	~0	124656.3

* actual force associated **with captured stream** tube on inlet surfaces from i to ci!

breakdown for inlet: F_x contribution from vehicle forebody surface ('upper') = 9295 N

F_y " " " " " " = 47817 N

F_x contribution " cowl (top) surface 2 to ci = -2226 N

F_y " " " " = -31833 N

Fluids summary: β is shock angle, θ is turning angle (if not relevant to a station or region, enter X)

Angle of flow from x (flight dir.)

Region	T_t	P_t	β	θ	M	P	T	$\lvert\vec{V}\rvert$	u	v	Angle of flow from x (flight dir.)
Free-stream	4856	5.0312×10^7	—	—	10	1185.5	231.24	3048	3048	0	(0)
Region downstream of incident inlet shock	4856	2.19×10^7	15.493°	11°	6.36	9670	535	2946	2892	-562.1	(-11°)
Region downstream of reflected inlet shock (ci)	4855	1.9753×10^7	14.327°	7°	5.31	26303	732	2878	2871	-200.8	(-4°)
Combustor exit (ce)	6583	1.55×10^6	—	—	2.27	129028	3236	2593	2587	-180.9	(-4°)
Nozzle exit (e)	6583	1.55×10^6	—	—	4.58	4847	1267	3268	3260	-228	-(4°)
Top surface of vehicle	4856	5.0312×10^7	expansion	-0.497°	10.18	1048	223.3	3051	3050.9	-26.5	-(0.5°)
Bottom of wing	4856	2.906×10^7	13.384°	9°	6.97	9213	453.3	2974	2937.4	-465	(-9°)
Top of wing	4856	5.03117×10^7	expansion	-9°	14.85	82	107.7	3088	3050	-483	(-9°)
Cowl bottom (bottom of vehicle)	4856	4.66×10^7	8.653°	4°	8.62	2933	306	3023	3016	-210.9	(-4°)