16.50 Propulsion Systems
Spring 2012

Quiz 1 March 18, 2011

One hour, open book, open notes

TRUE-FALSE QUESTIONS:

Give an explanation for your answer in no more than 2 lines. For each question,

Right answer, valid explanation	4-5 points
Right answer, bad explanation	1-3 points
Right answer, no explanation	0 points
Wrong answer, some coherent argument	1-2 points
Wrong answer, no explanation (or bad explanation)	0 points

		T	F
Q1	The larger the weight/thrust ratio of a rocket engine, the higher the optimum initial acceleration of the vehicle. *With a heavy engine, increasing a_0 would reduce payload more than the lowered ΔV_g would reduce it.*		√
Q2	For a satellite in an elliptical orbit about Earth, the minimum ΔV required to escape occurs at perigee. *The speed is highest at perigee, i.e. closer to escape velocity.*	√	
Q3	The maximum payload that can be carried over a given ΔV with an Electric Propulsion thrust system of a fixed specific mass α increases with the thrusting time chosen. *Long burn time implies lower power, so a lighter power system.*	√	
Q4	Since the flow speed at a choked throat is always sonic, and density is inversely proportional to temperature, the choked mass flow rate scales as $1/T_c$. *The other factor is speed of sound, which scales as $\sqrt{T_c}$ so, in the end, $\dot{m} \sim \frac{1}{\sqrt{T_c}}$*		√
Q5	A rocket nozzle is pressure-matched on the ground. As the rocket climbs and matching is lost, thrust decreases. *Pressure matching maximizes thrust <u>at fixed</u> P_0, but when P_0 is lowered (climb), thrust increases.*		√
Q6	If separation were somehow suppressed in an over-expanded nozzle with $P_e/P_0 < 0.4$, the thrust would increase. *Suppressing separation would re-introduce suction near the exit plane, reducing thrust.*		√
Q7	Reducing the throat area of a solid propellant rocket increases its thrust.	√	

	$P_c \sim \left(\frac{A_b}{A^*}\right)^{\frac{1}{1-n}}$ *and* $F \sim P_c A^* \sim A^{*\lambda - \frac{1}{1-n}} = A^{*\frac{-n}{1-n}}$ *So, less A^*, more thrust.*		
Q8	In an externally heated rocket (like a nuclear or solar thermal rocket), dissociation of the gas increases thrust (for fixed chamber temperature and pressure). *If T_c is fixed, dissociation allows addition of extra heat, part of which is converted to jet velocity.*	√	
Q9	In a chemical (combustion) rocket, dissociation of the gas increases thrust (for fixed chamber pressure). *In this case, there is no extra heat to be had, so dissociation lowers T_c. Even if the heat of dissociation is recovered in the expansion, it is recovered at lower P.*		√
Q10	Frozen flow expansion implies $\gamma = constant$. *The c_p of each component species still changes with T, so even at constant composition $\gamma = \gamma(T)$.*		√
Q11	Of the two mechanisms affecting ablative cooling, heat absorption by vaporization of the surface material is dominant. *Relatively little gas is generated at the surface, so its effect on S_t is fairly small. The main effect is the heat absorbed in the decomposition.*	√	
Q12	Jet engines operate fuel-lean in order to maximize specific impulse. *They operate lean to protect the turbine.*		√

PROBLEM (40% of grade)

In a LOX-Kerosene rocket the gas-side "film coefficient", $h_g \equiv q_w/(T_c - T_{wh})$ is estimated to be $1.4 \times \frac{10^4 W}{m^2}/K$ when the chamber pressure is $P_c = 100\ atm.$, the chamber temperature is $T_c = 3300\ K$, and the hot-side wall temperature is $T_{wh} = 800K$. The first wall, separating the gas from the coolant, is a $2\ mm$ plate of Copper/Tungsten (thermal conductivity $k = 300W/m/K$. The coolant is the kerosene fuel, and it is estimated to be at $T_l = 430K$ when it arrives at the throat section after cooling the nozzle skirt.

a) Calculate the heat flux q_w at the throat.

$$q_w = h_g(T_c - T_{wh}) = 1.4 \times 10^4(3300 - 800) = \boxed{3.5 \times 10^7 W/m^2}$$

b) By equating the same heat flux to that crossing the first wall, calculate the cool-side wall temperature T_{wc}.

$$q_w = \frac{k_w(T_{wh} - T_{wc})}{\delta} \rightarrow T_{wc} = T_{wh} - \frac{\delta}{k_w} q_w$$

$$T_{wc} = \frac{2\times10^{-3}}{300}\left(3.5 \times 10^7\right) = \boxed{567K}$$

c) By also equating q_w to the heat flux through the liquid-side boundary layer, calculate the required liquid-side film coefficient, h_l.

$q_w = h_l(T_{wc} - T_l) \rightarrow h_l = \frac{q_w}{T_{wc}-T_l} = \frac{3.5\times10^7}{567-430} =$ $\boxed{2.56\times10^5 \frac{W}{m^2K}}$

d) Assuming for the liquid $\rho_l = 800 kg/m^3$ and a specific heat $c_l = 1900\ J/kg/K$, and taking the liquid-side Stanton number to be 0.0015, calculate the implied liquid velocity u_l in the cooling passages.

$h_l = \rho_l u_l c_l (St_l)$

$u_l = \frac{2.56\times10^5}{800\times1900\times1.5\times10^{-3}} =$ $\boxed{112\ m/s}$

e) **(For 10 points of extra credit)** If, due to excessive pressure drops, the maximum liquid velocity is $80\ m/s$, what would be the maximum chamber pressure P_c compatible with these conditions?

From Bartz's equation, $q_w \sim h_g \sim (P_a)^{0.8}$, *so* $q_w = 3.5\times10^7\left(\frac{P_c}{100}\right)^{0.8}$

$T_{wc} = 800 - \frac{0.002}{300}(3.5\times10^7)\left(\frac{P_c}{100}\right)^{0.8} = 800 - 233\left(\frac{P_c}{100}\right)^{0.8}$

With $u_e = 80\frac{m}{s}$,

$$3.5\times10^7\left(\frac{P_c}{100}\right)^{0.8} = h_l\left(800 - 233\left(\frac{P_c}{100}\right)^{0.8} - 430\right)$$

$$= 800\times80\times1900\times1.5\times10^{-3}\left(370 - 233\left(\frac{P_c}{100}\right)^{0.8}\right)$$

$$3.5\times10^7\left(\frac{P_c}{100}\right)^{0.8} = 1.825\times10^5\left(370 - 233\left(\frac{P_c}{100}\right)^{0.8}\right)$$

$$\left(\frac{P_c}{100}\right)^{0.8} = \frac{1.825\times10^5\times370}{3.5\times10^7 + 1.825\times10^5\times233} = 0.871$$

$\boxed{P_c = 84.2\ atm}$

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