AAE 339: Aerospace Propulsion

HW6: Realistic Turbofan Cycle Analysis

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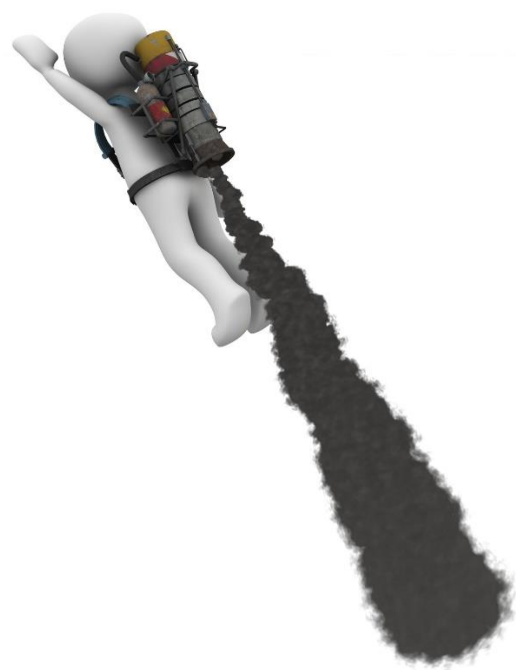
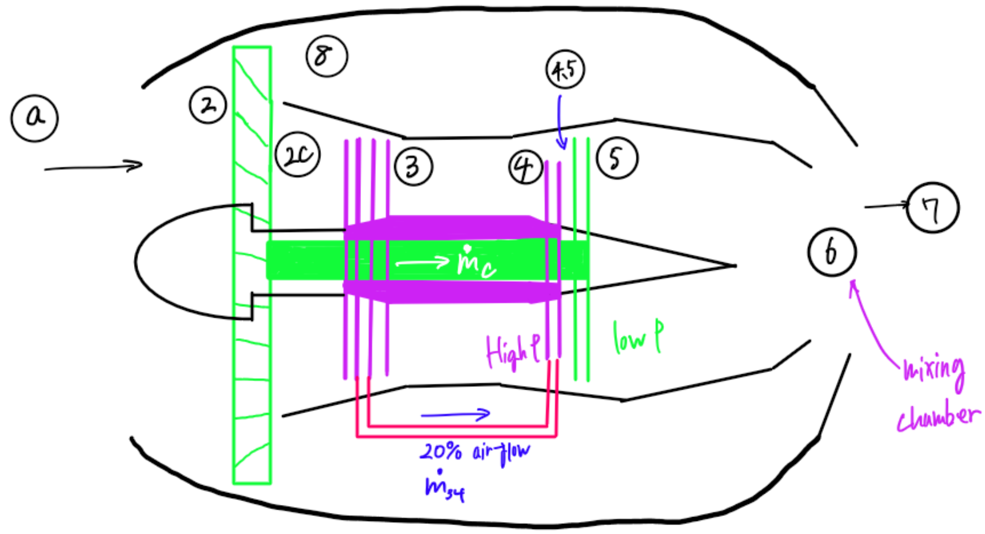


(a) Draw a neat schematic of the engine that clearly includes the changes noted above.

2 spool engine turbofan schematic



Given Properties

@ freestream

$h = 40{,}000\ ft \qquad M_a = 0.85$

$T_a = 389.97\ R = 216.65\ K$

$P_a = 3.9312 \times 10^2\ lb/ft = 18823\ Pa$

$R = 287\ J/kg\text{-}K$

$Q_r = 45{,}000\ kJ/kg \qquad \eta_b = 0.98 \qquad \eta_f = \dfrac{h_{08s} - h_{02}}{h_{08} - h_{02}} = \dfrac{T_{08s} - T_{02}}{T_{08} - T_{02}} = 0.85$

$\eta_d = \dfrac{h_{02s} - h_a}{h_{02} - h_a} = \dfrac{T_{02s} - T_a}{T_{02} - T_a} = 0.97, \quad \eta_c = \dfrac{h_{03s} - h_{02}}{h_{03} - h_{02}} = \dfrac{T_{03s} - T_{02}}{T_{03} - T_{02}} = 0.85$

$\eta_t = \dfrac{h_{04} - h_{05}}{h_{04} - h_{05s}} = \dfrac{T_{04} - T_{05}}{T_{04} - T_{05s}} = 0.90, \quad \eta_n = \dfrac{h_{06} - h_{7}}{h_{06} - h_{7s}} = \dfrac{T_{06} - T_{7}}{T_{06} - T_{7s}} = 0.98$

Burner Energy Equation

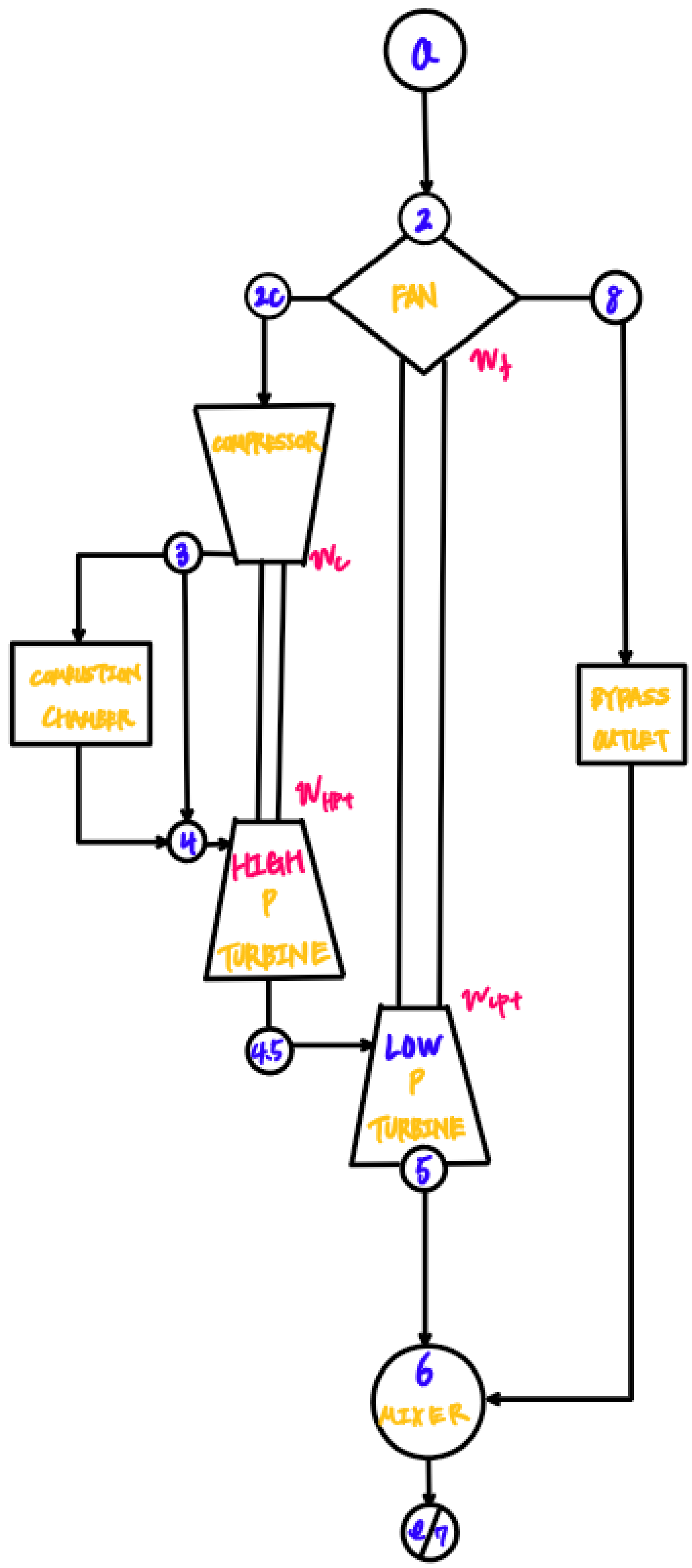
$(1+f)h_{04} = h_{03} + f\eta_b Q \quad \text{or} \quad (1+f)c_p T_{04} = c_p T_{03} + f\eta_b Q \quad \text{where } f = \dfrac{\dot{m}_f}{\dot{m}_a}$

and $P_{03} = P_{04}, \quad \dot{m}_a = 1.0\ kg/s, \quad T_{04} = 1800\ K$

$\beta = 8.5, \quad OPR = P_{03}/P_{02} = 42, \quad P_{02c} = 1.5 P_{02}$

(a) → (2) $\quad c_{p1} = 1.0\ kJ/kg\text{-}K \quad \gamma_1 = 1.4$

(2c) ⇝ $\quad c_{p2} = 1.10\ kJ/kg\text{-}K \quad \gamma_2 = 1.35$



a
2
2c
FAN
8
w_f
COMPRESSOR
3
w_c
COMBUSTION
CHAMBER
4
w_{HPt}
HIGH
P
TURBINE
BYPASS
OUTLET
w_{LPt}
4.5
LOW
P
TURBINE
5
6
MIXER
e/7

To solve (b) we use answers from part (d)

(b) Calculate the specific work required by the fan and the compressor.

Use stagnation properties at the stations

2 2c 3 8

$T_{02} = 248.92 K$ $T_{03} = 741.44 K$

$T_{02c} = T_{08} = 281.39 K$

fan

$w_f = (1+\beta) C_{p2} (T_{08} - T_{02})$

$w_f = 3.3790 \times 10^5 \frac{J}{kg}$

compressor

$w_c = C_{p2} (T_{03} - T_{02c})$

$w_c = 5.0409 \times 10^5 \frac{J}{kg}$

$$\boxed{\begin{aligned} w_f &= 337.90 \frac{kJ}{kg} \\ w_c &= 504.09 \frac{kJ}{kg} \end{aligned}}$$

(c) Determine the fuel-air ratio in the combustor.

since, there is air bleeding from the Compressor to cool the turbine.

$$\dot{m}_a = \dot{m}_{34} + \dot{m}_c$$

since $\delta = \frac{\dot{m}_{34}}{\dot{m}_a} = 0.2$, $\varepsilon = \frac{\dot{m}_c}{\dot{m}_a} = 0.8$

now, the Burner Energy Equation can be rewritten as

$$\int_{cs} (h_0)\rho(\bar{u}\cdot\bar{n})\,dA = \dot{Q} - \cancel{W_{34}}^{\,0}$$

$$(\dot{m}_c + \dot{m}_f)h_{04} - (\dot{m}_c)h_{03} = \dot{m}_f \eta_b Q_r$$

$$\Longleftrightarrow (\varepsilon + f)h_{04} - \varepsilon h_{03} = f\eta_b Q_r$$

$$(\varepsilon + f)C_{p2}T_{04} - \varepsilon C_{p2}T_{03} = f\eta_b Q_r$$

$$\varepsilon C_{p2}(T_{04} - T_{03}) = f(\eta_b Q_r - C_{p2}T_{04})$$

$$f = \frac{\varepsilon C_{p2}(T_{04} - T_{03})}{\eta_b Q_r - C_{p2}T_{04}}$$

$$f = \frac{0.8\left(1.1\times10^3\frac{J}{kg\text{-}K}\right)(1800K - 741.44K)}{0.98\left(45000\times10^3\frac{J}{kg}\right) - \left(1.1\times10^3\frac{J}{kg\text{-}K}\right)(1800K)}$$

$$\boxed{f = 0.022116}$$

(d) Calculate stagnation conditions in the free stream, at the engine face (2), at the entry of the bypass duct and compressor, at the combustor inlet (3), at the inlets to the turbines (4 and 4.5), exit of the low-pressure turbine (5), at the exit of the mixing section (call it 6), and engine exit (7).

MATLAB was utilised for calculations ; code is in Appendix

<i> @ freestream.

same as p1 the properties are from textbook appendix

$$T_a = 389.97 \ R = 216.65 \ K$$
$$P_a = 3.9312 \times 10^2 \ lb/ft^2 = 18823 \ Pa$$

then
$$P_{0a} = P_a \left[1 + \frac{\gamma_i - 1}{2} M_a^2\right]^{\frac{\gamma_i}{\gamma_i - 1}}$$
$$P_{0a} = (18823 \, Pa)\left[1 + \frac{1.4-1}{2}(0.85)^2\right]^{\frac{1.4}{1.4-1}} \simeq 30189 \ Pa$$
$$T_{0a} = T_a\left[1 + \frac{\gamma_i - 1}{2} M_a^2\right]$$
$$T_{0a} \simeq 247.96 \ K$$

$$\boxed{\begin{aligned} P_{0a} &= 30189 \, Pa \\ T_{0a} &= 247.96 \, K \end{aligned}}$$

<ii> engine entry / compressor inlet (2)

the stagnation temperature and pressure does not change from when it entered the engine, thus

$$P_{02} = 30189 \ Pa$$
$$T_{02} = 247.96 K$$

now, from η_d, we know that

$$T_{02s} = T_{0a} + \frac{T_{02} - T_{01}}{\eta_d} = 247.0167$$

now from isentropic relations

$$\left(\frac{P_{02}}{P_{0a}}\right) = \left(\frac{T_{02s}}{T_{0a}}\right)^{\gamma_i/\gamma_i - 1} \Rightarrow P_{02} = 29790 \ Pa$$

Bypass duct inlet (8)

$$P_{08} = P_{02c} = 45283 \, Pa$$
$$T_{08} = T_{02c} = 281.39 \, K$$

in front of the fan

$$\boxed{\begin{aligned} P_{02} &= 29790 \, Pa \\ T_{02} &= 247.02 \, K \end{aligned}}$$

$$\boxed{P_{02c} = 1.5 P_{02} = 44686 \ Pa}$$

then

$$\frac{T_{02cs}}{T_{02}} = \left(\frac{P_{02c}}{P_{02}}\right)^{\frac{\gamma_2-1}{\gamma_2}}$$

$$T_{02cs} = T_{02}\left(\frac{P_{02c}}{P_{02}}\right)^{\frac{\gamma_2-1}{\gamma_2}} = (248.93\,K)\left(\frac{45283.5\,Pa}{30189\,Pa}\right)^{\frac{0.35}{1.35}}$$

$$T_{02cs} = 275.44\ K$$

from η_f

$$T_{02c} = T_{02} + \frac{T_{02cs} - T_{02}}{\eta_f}$$

$$\boxed{T_{02c} = 280.29\ K}$$

<iii> Combustor inlet (3)

from the relations $\frac{P_{03}}{P_{02}} = 42$, $\frac{P_{02c}}{P_{02}} = \frac{3}{2}$

$$\frac{P_{03}}{P_{02c}} = \frac{P_{03}}{P_{02}} \cdot \frac{P_{02}}{P_{02c}} = 42 \cdot \frac{2}{3} = 28$$

then,

$$\boxed{P_{03} = 28\,P_{02c} = 28\,(44686\,Pa) = 1.2512 \times 10^6\,Pa}$$

next, from isentropic relations

$$\frac{T_{03s}}{T_{02c}} = \left(\frac{P_{03}}{P_{02c}}\right)^{\frac{\gamma_2 - 1}{\gamma_2}}$$

$$T_{03s} = T_{02c}\left(\frac{P_{03}}{P_{02c}}\right)^{\frac{\gamma_2-1}{\gamma_2}} = (281.39\ \mathrm{K})\left(\frac{1.2679\times10^6\ \mathrm{Pa}}{44686\ \mathrm{Pa}}\right)^{\frac{0.35}{1.35}}$$

$$T_{03s} = 664.96\ \mathrm{K}$$

now using η_c,

$$T_{03} = T_{02} + \frac{T_{03s} - T_{02}}{\eta_c}$$

$$\boxed{T_{03} = 738.55\ \mathrm{K}}$$

<iv-a> High p turbine inlet (4)

it is given that the turbine inlet is

$$\boxed{T_{04} = 1800\ \mathrm{K}}$$

and it is also given that

$$\boxed{P_{04} = P_{03} = 1.2512\times10^6\ \mathrm{Pa}}$$

<iv-b> Intermediate of High P and Low P turbine (4.5)

from the fact that

work of High P turbine $= -w_c$

$$\varepsilon C_{p_2}(T_{045} - T_{04}) + \delta C_{p_2}(T_{045} - T_{03}) = -w_c$$

$$\varepsilon T_{045} + \delta T_{045} - \varepsilon T_{04} - \delta T_{03} = \frac{-w_c}{C_{p_2}}$$

$$\because \varepsilon + \delta = 1 \implies T_{045} = \varepsilon T_{04} + \delta T_{03} - \frac{w_c}{C_{p_2}}$$

$$\boxed{T_{045} = 1129.4\ \mathrm{K}}$$

<v> exit of Low P turbine (5)

since

work of low P turbine = $-w_f$

$$c_{p2}(T_{05} - T_{045}) = -w_f$$

$$T_{05} = T_{045} - \frac{w_f}{c_{p2}} \quad \cdots ②$$

$$\boxed{T_{05} = 822.27\ K}$$

$$\eta_t = \frac{T_{04} - T_{05}}{T_{04} - T_{05s}}$$

$$\eta_{HP,t} = \frac{T_{04} - T_{045}}{T_{04} - T_{045s}}$$

$$\eta_{LP,t} = \frac{T_{045} - T_{05}}{T_{045} - T_{05s}}$$

if $\eta_t = \eta_{HP,t} = \eta_{LP,T}$

$$T_{045s} = T_{04} - \frac{T_{04} - T_{045}}{\eta_{HP,t}} = 1054.9\ K$$

$$\frac{P_{045}}{P_{04}} = \left(\frac{T_{045s}}{T_{04}}\right)^{\frac{\gamma_2}{\gamma_2 - 1}}$$

$$P_{045} = P_{04}\left(\frac{T_{045s}}{T_{04}}\right)^{\frac{\gamma_2}{\gamma_2 - 1}}$$

$$\boxed{P_{045} = 1.5933 \times 10^5\ Pa}$$

$$T_{05s} = T_{045} - \frac{T_{045} - T_{05}}{\eta_{LP,t}} = 788.14\,K$$

$$\frac{P_{05}}{P_{045}} = \left(\frac{T_{05s}}{T_{045}}\right)^{\frac{\gamma_2}{\gamma_2-1}}$$

$$P_{05} = P_{045}\left(\frac{T_{05s}}{T_{045}}\right)^{\frac{\gamma_2}{\gamma_2-1}}$$

$$\boxed{P_{05} = 3.9771 \times 10^4\ Pa}$$

<vi> mixing chamber (6)

assuming no energy/heat transfer

using the 1^{st} law of thermodynamics

steady

$$\cancel{\frac{\partial}{\partial t}}\int_{CV}\left(e+\frac{u^2}{2}+gz\right)\rho\, d\forall + \int_{CS}\left(h+\frac{u^2}{2}+gz\right)\rho(\bar{u}\cdot\bar{n})dA = \cancel{\dot{Q}}^{0} - \cancel{\dot{W}}^{0}$$

$$\dot{m}_6 h_{06} - \dot{m}_5 h_{05} - \dot{m}_8 h_{08} = 0$$

since $\dot{m}_6 = \dot{m}_5 + \dot{m}_8$, $\dot{m}_5 = \dot{m}_a$, $\dot{m}_8 = \beta \dot{m}_a$

$$\Longleftrightarrow \quad (1+\beta)h_{06} - h_{05} - \beta h_{08} = 0$$

$$\Longleftrightarrow \quad (1+\beta)C_{p2}T_{06} - C_{p2}T_{05} - \beta C_{p2}T_{08} = 0$$

$$\Longleftrightarrow \quad (1+\beta)T_{06} - T_{05} - \beta T_{08} = 0$$

$$T_{06} = \frac{T_{05} + \beta T_{08}}{1+\beta}$$

$$\boxed{T_{06} = 377.34\ K}$$

also using the 2^{nd} law

$$\cancel{\frac{\partial S}{\partial t}\Big|_{sys}}^{\text{steady}} = \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \overbrace{\cancel{\sum_j \frac{\dot{Q}_j}{T_{j,cs}}}^{0} + \cancel{\dot{\sigma}_{gen}}^{0}}^{\text{isentropic}}$$

$$\Rightarrow \Delta S_{5\to6} + \Delta S_{8\to6}$$

$$= \dot{m}_5(s_6 - s_5) + \dot{m}_8(s_6 - s_8)$$

Since $\dot{m}_5 = \dot{m}_a$ and $\dot{m}_8 = \beta \dot{m}_a$

also $\Delta S_{12} = c_p \ln \frac{T_{02}}{T_{01}} - R \ln \frac{P_{02}}{P_{01}}$

(* entropy is same for static and stagnation
https://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node50.html
)

$$= c_p \ln \frac{T_{06}}{T_{05}} - R \ln \frac{P_{06}}{P_{05}} + \beta\left(c_p \ln \frac{T_{06}}{T_{08}} - R \ln \frac{P_{06}}{P_{08}}\right)$$

$$= \emptyset$$

$$\Leftrightarrow \ln\left(\frac{P_{06}}{P_{05}}\right)^R + \ln\left(\frac{P_{06}}{P_{08}}\right)^{\beta R} = \ln\left(\frac{T_{06}}{T_{05}}\right)^{c_{p2}} + \ln\left(\frac{T_{06}}{T_{08}}\right)^{\beta c_{p2}}$$

$$\left(\frac{P_{06}}{P_{05}}\right)^R \left(\frac{P_{06}}{P_{08}}\right)^{\beta R} = \left(\frac{T_{06}}{T_{05}}\right)^{c_{p2}} \left(\frac{T_{06}}{T_{08}}\right)^{\beta c_{p2}}$$

$$\frac{P_{06}^{(1+\beta)R}}{P_{05}^{R}\, P_{08}^{\beta R}} = \frac{T_{06}^{(1+\beta)c_{p2}}}{T_{05}^{c_{p2}}\, T_{08}^{\beta c_{p2}}}$$

$$P_{06}^{(1+\beta)R} = \frac{P_{05}^{R}\, P_{08}^{\beta R}}{T_{05}^{c_{p2}}\, T_{08}^{\beta c_{p2}}} T_{06}^{(1+\beta)c_{p2}}$$

$$P_{06} = \left[\frac{P_{05}^{R}\, P_{08}^{\beta R}}{T_{05}^{c_{p2}}\, T_{08}^{\beta c_{p2}}}\right]^{\frac{1}{(1+\beta)R}} T_{06}^{\frac{c_{p2}}{R}}$$

$$\boxed{P_{06} = 58164 \text{ Pa}}$$

(vii) engine exit (7)

$P_7 = P_a = 18823\ Pa$, because we assume Isentropic

since stagnation temperature and pressure remain constant from (6)

$$\boxed{\begin{aligned} P_{07} &= P_{06} = 58164\ Pa \\ T_{07} &= 377.34\ K \end{aligned}}$$

(e) Calculate temperature, pressure, and velocity at engine exit 7 (T_7, p_7, u_7).

from P_{07} & P_7 $\boxed{P_7 = 18823\ Pa}$

$$\frac{P_{07}}{P_7} = \left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{\frac{\gamma_2}{\gamma_2 - 1}}$$

$$\left(\frac{P_{07}}{P_7}\right)^{\frac{\gamma_2 - 1}{\gamma_2}} = 1 + \frac{\gamma - 1}{2} M_e^2$$

$$\frac{\gamma - 1}{2} M_e^2 = \left(\frac{P_{07}}{P_7}\right)^{\frac{\gamma_2 - 1}{\gamma_2}} - 1$$

$$M_e = \sqrt{\frac{2}{\gamma_2 - 1}\left[\left(\frac{P_{07}}{P_7}\right)^{\frac{\gamma_2 - 1}{\gamma_2}} - 1\right]}$$

$$M_e = 1.3934$$

now

$$\frac{T_{07}}{T_{7s}} = 1 + \frac{\gamma_2 - 1}{2} M_e^2$$

$$T_{7s} = \frac{T_{07}}{1 + \frac{\gamma_2 - 1}{2} M_e^2}$$

$$\boxed{T_{7s} = 251.79\ K}$$

then using η_n

$$T_7 = T_{06} - \eta_n (T_{06} - T_{7s})$$

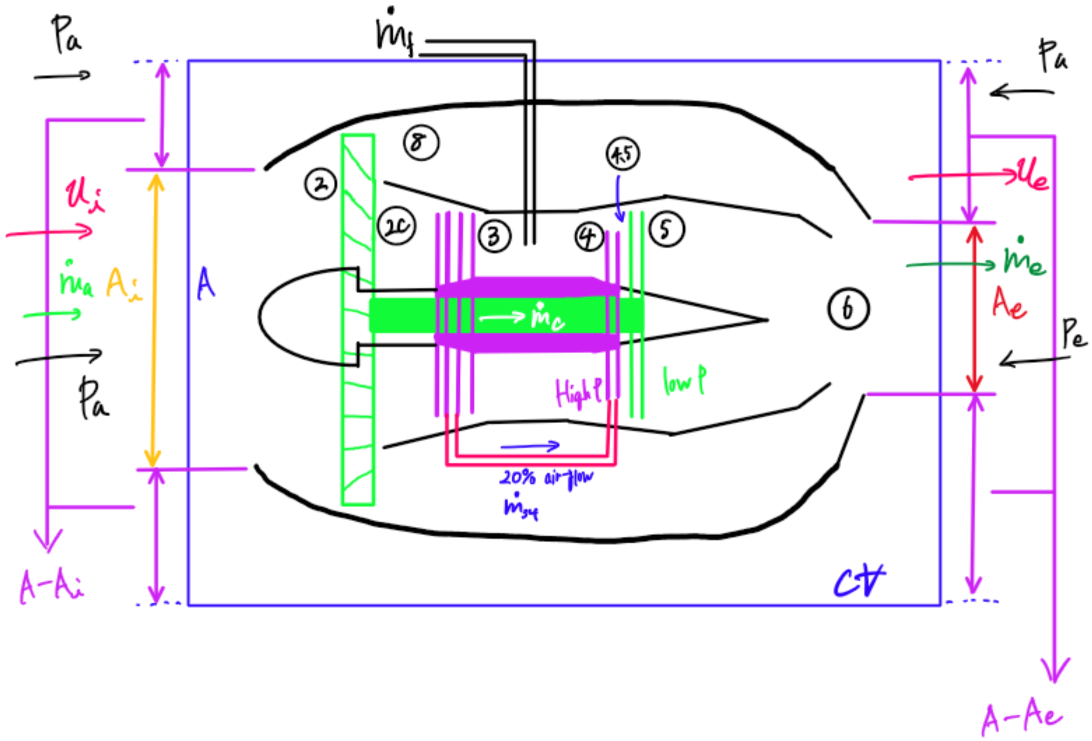
$$\boxed{T_7 = 253.50\ K}$$

lastly

$$u_7 = M_e \sqrt{\gamma_2 R T_7}$$

$$\boxed{u_7 = 436.68\ m/s}$$

(f) Not everyone was able to correctly develop an equation for thrust in Exam 1, so let's do it again. Draw a control volume around the engine, clearly showing control surfaces and external forces. Starting with the conservation equations, and using your CV, derive an equation for thrust.



from momentum conservation

$$\cancel{\frac{\partial}{\partial t}\int_{CV}\rho\bar{u}\,d\forall}^{\text{steady}} + \int_{CS}\rho\bar{u}(\bar{u}\cdot\bar{n})\,dA = \Sigma\bar{F}$$

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LHS

$$(\dot{m}_a+\dot{m}_b+\dot{m}_f)u_e - (\dot{m}_a+\dot{m}_b)u_i$$

$$= \dot{m}_a\left[(1+\beta+f)u_e - u_i - \beta u_i\right]$$

$$= \dot{m}_a\left[(1+f)u_e - u_i + \beta(u_e - u_i)\right]$$

RHS

$$p_a A - p_e A_e - p_a(A - A_e)$$

$$= p_a A - p_e A_e - p_a A + p_a A_e = 0$$

Thus,

$$\boxed{T = \dot{m}_a\left[(1+f)u_e - u_i + \beta(u_e - u_i)\right]}$$

(g) Calculate specific thrust and specific fuel consumption, and compare to results from HW5, #2.

$$ST = \frac{T}{\dot{m}_a} = (1+f)u_e - u_i + \beta(u_e - u_i)$$

$$u_i = M_a\sqrt{\gamma R T_a}$$

$$u_i = 0.85\sqrt{1.4\,(287\ \mathrm{J/kg\cdot K})\,(216.65\ \mathrm{K})}$$

$$u_i = 250.79\ \mathrm{m/s}$$

plug in all the numbers

$u_e = 436.68$ m/s

$f = 0.0222$

$\beta = 8.5$

$$\boxed{ST = 1775.7\ \mathrm{m/s}}$$

from HW5 (2) solutions

The $ST' = 1434.5$ m/s

we have a

$$\frac{ST - ST'}{ST'} \times 100 = 23.79\%$$

improvement from HW5 (2)

Appendix

AAE 339 HW6 MATLAB CODE

```
close all; clear all; clc

% Given properties
Ma = 0.85;
gamma1 = 1.4;
Cp1 = 1.0*10^3;  % [J/kg/K]
gamma2 = 1.35;
Cp2 = 1.10*10^3;  % [J/kg/K]
R = 287;  % [J/kg/K]
Qr = 45000*10^3;  % [J/kg]
eta_d = 0.97;
eta_c = 0.85;
eta_f = eta_c;
eta_t = 0.90;
eta_n = 0.98;
eta_b = 0.98;
beta = 8.5;
Po3_Po2_ratio = 42;
Po2c_Po2_ratio = 1.5;
To4 = 1800; % [K]

% freestream (a)
Ta = 216.65;  % [K]
Pa = 18823;  % [Pa]
Poa = p_from_M_and_gamma(Pa, Ma, gamma1, "stagnation")
Toa = T_from_M_and_gamma(Ta, Ma, gamma1, "stagnation")

% engine entry (2)
To2 = Toa
To2s = T_from_adiabatic_eff_stagnation(Ta, To2, eta_d, "diffuser")
Po2 = P_from_isentropic_relation(Poa, To2s, Toa, gamma1)

% compressor inlet (2c)
Po2c = Po2c_Po2_ratio*Po2
To2cs = T_from_isentropic_relation(To2, Po2c, Po2, gamma2)
To2c = T_from_adiabatic_eff_static(To2, To2cs, eta_f, "fan")

% combustor inlet (3)
Po3_Po2c_ratio = Po3_Po2_ratio/Po2c_Po2_ratio
Po3 = Po3_Po2c_ratio*Po2c
To3s = T_from_isentropic_relation(To2c, Po3, Po2c, gamma2)
To3 = T_from_adiabatic_eff_static(To2, To3s, eta_c, "compressor")

% combustor exit/High pressure turbine inlet (4)
To4 = 1800  % [K]
Po4 = Po3

% bypass duct inlet (8)
Po8 = Po2c
```

```
To8 = To2c

% calculate the work done by fan and compressor
Wf = (1 + beta) * Cp2 * (To8 - To2)
Wc = Cp2 * (To3 - To2c)

% calculate the fuel-air-ratio
delta = 0.2;
epsilon = 0.8;
f = epsilon*Cp2*(To4 - To3)/(eta_b*Qr - Cp2*To4)
disp(vpa(f, 7))

% intermediate of high pressure and low pressure turbines (4.5)
To45 = epsilon*To4 + delta*To3 - Wc/Cp2
eta_HP_t = eta_t;
To45s = To4 - (To4 - To45)/eta_HP_t
Po45 = P_from_isentropic_relation(Po4, To45s, To4, gamma2)

% exit of the low pressure turbine (5)
To5 = To45 - Wf/Cp2
eta_LP_t = eta_t;
To5s = To45 - (To45 - To5)/eta_LP_t
Po5 = P_from_isentropic_relation(Po45, To5s, To45, gamma2)

% mixing chamber (6)
Cp2_alt = Cp2/1000;
R_alt = R/1000;
To6 = (To5 + beta*To8)/(1 + beta)
a1 = Po5^R_alt;
a2 = Po8^(beta*R_alt);
a3 = To5^(Cp2_alt);
a4 = To8^(beta*Cp2_alt);
b1 = To6^(Cp2_alt/R_alt);
A1 = (a1*a2/a3/a4)^(1/(1 + beta)/R_alt);
Po6 = A1*b1

% Calculating properties at exit (7)
P7 = Pa
Po7 = Po6
To7 = To6
a1 = (Po7/Pa)^((gamma2 - 1)/gamma2) - 1;
Me = sqrt(2/(gamma2 - 1)*a1)
T7s = To7/(1 + (gamma2 - 1)/2*Me^2)
T7 = T_from_adiabatic_eff_static(To6, T7s, eta_n, "nozzle")
u7 = Me * sqrt(gamma2 * R * T7)

% calculate velocity at engine entry
ua = Ma*sqrt(gamma1*R*Ta)
% Specfic thrust
ST = (1 + f)*u7 - ua + beta*(u7 - ua)
imp = (ST - 1434.5)/1434.5*100
```

```
function  T2 = T_from_M_and_gamma(T1, M, gamma, type)
    if type == "stagnation"
        T2 = T1 * (1 + (gamma - 1) / 2 * M^2);
    elseif type == "static"
        T2 = T1 / (1 + (gamma - 1) / 2 * M^2);
    else
        disp("Error. Incorrect type. Type can only be 'stagnation' or 'static'.")
    end
end

function T2 = T_from_isentropic_relation(T1, P2, P1, gamma)
    T2 = T1 * (P2 / P1)^((gamma - 1)/ gamma);
end

function To2 = T_from_adiabatic_eff_static(To1, To2s, eta, type)
    if type == "diffuser" || type == "compressor" || type == "fan"
        To2 = To1 + (To2s - To1) / eta;
    elseif type == "nozzle" || type == "turbine"
        To2 = To1 - eta * (To1 - To2s);
    else
        disp("Error, incorrect type. Accepted types are 'diffuser,' " + ...
            "'compressor,' 'nozzle,' 'turbine,' or 'fan.'");
    end
end

function To2s = T_from_adiabatic_eff_stagnation(To1, To2, eta, type)
    if type == "diffuser" || type == "compressor" || type == "fan"
        To2s = To1 + (To2 - To1) * eta;
    elseif type == "nozzle" || type == "turbine"
        To2s = To1 - (To1 - To2) / eta;
    else
        disp("Error, incorrect type. Accepted types are 'diffuser,' " + ...
            "'compressor,' 'nozzle,' 'turbine,' or 'fan.'");
    end
end

function  p2 = p_from_M_and_gamma(p1, M, gamma, type)
    if type == "stagnation"
        p2 = p1 * (1 + (gamma - 1) / 2 * M^2)^(gamma/(gamma - 1));
    elseif type == "static"
        p2 = p1 / (1 + (gamma - 1) / 2 * M^2)^(gamma/(gamma - 1));
    else
        disp("Error. Incorrect type. Type can only be 'stagnation' or 'static'.")
    end
end

function P2 = P_from_isentropic_relation(P1, T2, T1, gamma)
    P2 = P1 * (T2 / T1)^(gamma / (gamma - 1));
end
```