OPERATING CHARACTERISTICS — SINGLE SHAFT GT @ FULL POWER

ENGINE INLET (ATM)
- $p_{ATM} = 14.7$ PSIA
- $T_{ATM} = 70°F$
- $\dot{m}_{AIR} = 4.08 \frac{lbm}{s}$

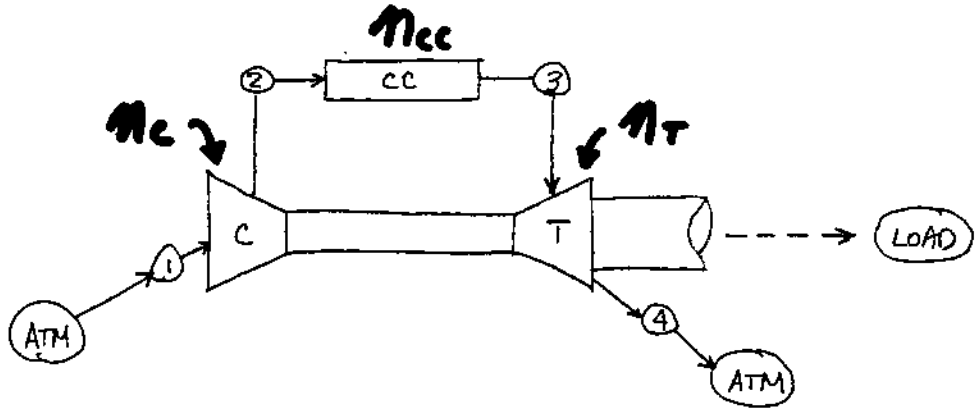
COMPRESSOR (1→2)
- INLET DUCT LOSS = 47 IN H_2O → BELOW p_{ATM}
- DISCHARGE PRESS = 63.3 PSIG
- DISCHARGE TEMP = 507°F

COMBUSTION CHAMBER (2→3)
- $\dot{m}_{FUEL} = 4.87 \frac{lbm}{MIN}$
- FUEL LHV = 18,300 $\frac{Btu}{lbm}$
- PRESS DROP = 3 PSI
  ↳ BELOW p_2

TURBINE (3→4)
- INLET TEMP = 1740°F
- DISCHARGE TEMP = 1161°F
- EXIT DUCT LOSS = 63.7 IN H_2O
  ↳ ABOVE p_{ATM}

OUTPUT SHAFT
- SPEED = N = 30,000 RPM
- TORQUE = τ = 52.52 FT·LBf

FIND:
a) THERMAL EFFICIENCY, η_{TH} [%]
b) NET INTERNAL HP, ihp [HP]
c) BRAKE HP, bhp [HP]
d) MECHANICAL LOSSES, LOSS$_{MECH}$
e) AIR FUEL RATIO, AFR
f) AIR RATE, AR
g) SPECIFIC FUEL CONSUMPTION, SFC (A.K.A. BRAKE SFC, BSFC)
h) OVERALL ENGINE EFFICIENCY, η_{OA} [%]



"SCHEMATIC" (A.K.A. COMPONENT DIAGRAM) HELPS VISUALIZE INFO.

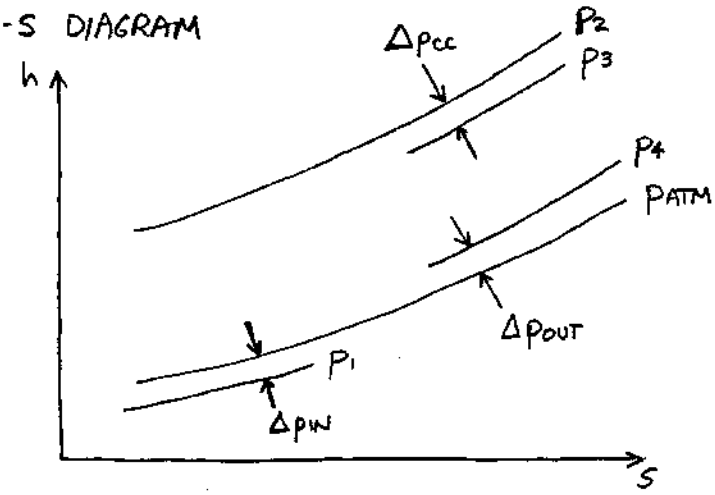
RECALL, 6 FACTORS COULD REDUCE "IDEAL" GT INTO "ACTUAL" GT

COMPONENT η	PRESSURE DROPS
① η_c	④ Δp_{IN}
② η_{cc}	⑤ Δp_{cc}
③ η_T	⑥ Δp_{OUT}

DUE TO η_c AND η_T, WE NO LONGER HAVE ISENTROPIC COMPRESSION (1→2) NOR DO WE HAVE ISENTROPIC EXPANSION (3→4), THAT IS COMPRESSOR WORK AND TURBINE WORK ARE NOT IDEAL ANYMORE.
— SO WE MUST ADD <u>TWO</u> NEW STATE PTS (2s, 4s)

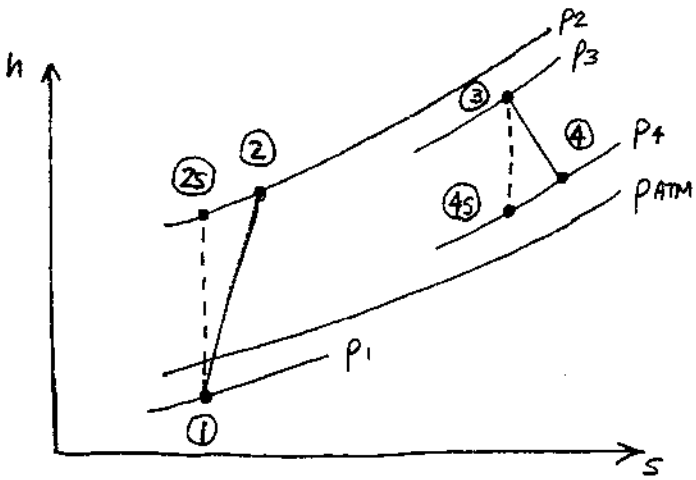
	①	2s	②	③	4s	④
p [PSIA]	___	___	___	___	___	___
T [°F]	___	___	___	___	___	___
h [Btu/lbm]	___	___	___	___	___	___
Pr	___	___	___	___	___	___

DRAW h-s DIAGRAM



START W/ PRESSURE LINES

YOU MUST LABEL PRESSURES ON THE h-s DIAGRAM



ADD ALL STATE PTS

1→2s AND 3→4s ARE PHANTOM LINES: PROCESSES DO NOT REALLY EXIST BUT MUST BE CALCULATED TO FIND 1→2 AND 3→4 USING η_c, η_T

NOW THAT WE CAN VISUALIZE THE h-s DIAGRAM, START FILLING IN THE STATE PT PROPERTY TABLE: (START W/ THE GIVEN INFO)

	1	2s	2	3	4s	4
p [PSIA]	13.0	78.0	78.0	75.0	17.0	17.0
T [°F]	70	—	507	1740	—	1161
h [$\frac{Btu}{lbm}$]	—	—	—	—	—	—
Pr	—	—	—	—	—	—

$p_1 \rightarrow$ $p_1 = p_{ATM} - \Delta p_{IN} = 14.7\ PSIA - 47\ IN\ H_2O \left(\frac{.0361\ PSI}{1\ IN\ H_2O}\right) = 13.0\ PSIA$

$T_1 \rightarrow$ GIVEN

$p_2 \rightarrow$ $p_2 = 63.3\ PSIG \rightarrow p_2 = p_{ATM} + 63.3\ PSIG = 14.7 + 63.3 = 78.0\ PSIA$

$p_{2s} \rightarrow$ $p_{2s} = p_2$

$T_2 \rightarrow$ GIVEN (COMPRESS. DISCHARGE PRESS)

$p_3 \rightarrow$ $p_3 = p_2 - \Delta p_{CC} = 78.0\ PSIA - 3\ PSI = 75.0\ PSIA$

$T_3 \rightarrow$ GIVEN (TURBINE <u>INLET</u> TEMP)

$T_4 \rightarrow$ GIVEN (TURBINE <u>DISCHARGE</u> TEMP)

$p_4 \rightarrow$ $p_4 = p_{ATM} + \Delta p_{OUT} = 14.7\ PSIA + 63.7\ IN\ H_2O \left(\frac{.0361\ PSI}{1\ IN\ H_2O}\right) = 17.0\ PSIA$

$p_{4s} \rightarrow$ $p_{4s} = p_4$

LOOKING AT THE ABOVE INCOMPLETE TABLE, WE CAN USE THE AIR TABLES TO FIND ALL PROPERTIES (EXCEPT PRESSURE) — <u>IF</u> WE KNOW T, h, OR Pr FOR A STATE POINT.

LOOK AT 2s AND 4s, VERY LITTLE IS KNOWN EXCEPT PRESSURE. WE MUST USE THIS <u>ISENTROPIC</u> RELATION TO START:

$1 \rightarrow 2s$ ISENTROPIC, SO:

$$\frac{p_{2s}}{p_1} = \frac{Pr_{2s}}{Pr_1}$$

$$Pr_{2s} = Pr_1 \left(\frac{p_{2s}}{p_1}\right), \quad p_{2s} = p_2$$

SIMILARLY:

$3 \rightarrow 4s$ ISENTROPIC, SO:

$$\frac{p_3}{p_{4s}} = \frac{Pr_3}{Pr_{4s}}$$

$$Pr_{4s} = Pr_3 \left(\frac{p_{4s}}{p_3}\right), \quad p_{4s} = p_4$$

NOW WE COMPLETE THE STATE PT PROPERTY TABLE:

	1	2s	2	3	4s	4
p [PSIA]	13.0	78.0	78.0	75.0	17.0	17.0
T [°F]	70	421	507	1740	1055	1161
h [$\frac{Btu}{lbm}$]	126.7	211.6	232.8	560.3	373.1	401.3
Pr	1.299	7.794	10.897	256.039	58.035	75.430

$h_1, Pr_1 \rightarrow$ AIR TABLES @ $T_1 = 70°F$ $\quad h_1 = 126.7 \frac{Btu}{lbm}$ $\quad Pr_1 = 1.299$

$Pr_{2s} \rightarrow$ $\underbrace{Pr_{2s} = Pr_1\left(\frac{p_{2s}}{p_1}\right)} = 1.299\left(\frac{78}{13}\right) = 7.794$

$T_{2s}, h_{2s} \rightarrow$ AIR TABLES @ $Pr_{2s} = 7.794$ $\quad T_{2s} = 421°F$ $\quad h_{2s} = 211.6 \frac{Btu}{lbm}$

$h_2, Pr_2 \rightarrow$ AIR TABLES @ $T_2 = 507°F$ $\quad h_2 = 232.8 \frac{Btu}{lbm}$ $\quad Pr_2 = 10.897$

$h_3, Pr_3 \rightarrow$ AIR TABLES @ $T_3 = 1740°F$ $\quad h_3 = 560.3 \frac{Btu}{lbm}$ $\quad Pr_3 = 256.039$

$Pr_{4s} \rightarrow$ $\underbrace{Pr_{4s} = Pr_3\left(\frac{p_{4s}}{p_3}\right)} = 256.039\left(\frac{17}{75}\right) = 58.035$

$T_{4s}, h_{4s} \rightarrow$ AIR TABLES @ $Pr_{4s} = 58.035$ $\quad T_{4s} = 1055°F$ $\quad h_{4s} = 373.1 \frac{Btu}{lbm}$

$h_4, Pr_4 \rightarrow$ AIR TABLES @ $T_4 = 1161°F$ $\quad h_4 = 401.3 \frac{Btu}{lbm}$ $\quad Pr_4 = 75.430$

NOW THAT ALL PROPERTIES ARE KNOWN, WE START THE ANALYSIS.

(a) THERMAL EFFICIENCY, $\eta_{TH} = \frac{W_{NET}}{q_S} = \frac{q_{NET}}{q_S}$

FIRST WAY: $W_{NET} = W_T - W_C = (h_3 - h_4) - (h_2 - h_1)$
$= (560.3 - 401.3) - (232.8 - 126.7)$
$W_{NET} = 52.9 \frac{Btu}{lbm}$

$q_S = q_{23} = h_3 - h_2 = 560.3 - 232.8 = 327.5 \frac{Btu}{lbm}$

$\eta_{TH} = \frac{52.9}{327.5} \rightarrow \boxed{\eta_{TH} = 16.2\%}$

SECOND WAY: $q_{NET} = q_S - q_R = (h_3 - h_2) - (h_4 - h_1)$
$= (560.3 - 232.8) - (401.3 - 126.7)$
$q_{NET} = 52.9 \frac{Btu}{lbm}$

$\eta_{TH} = \frac{52.9}{327.5} \rightarrow \boxed{\eta_{TH} = 16.2\%}$

CONTINUE ANALYSIS:

(b) NET INTERNAL HP (ihp), [HP]

$$ihp = \dot{m}_{AIR}(w_{NET}) \qquad [\text{NOTE: } \dot{m}_{AIR} \text{ WAS GIVEN}]$$

$$= 4.08\ \frac{LBm}{S}\left(52.9\ \frac{Btu}{LBm}\right)\left(\frac{1\ HP}{.707\ Btu/s}\right)$$

$$\boxed{ihp = 305.3\ HP}$$

(c) BRAKE HORSEPOWER (bhp), [HP]

→ NORMALLY WE USE: $\eta_{MECH} = \frac{bhp}{ihp}$, BUT DON'T KNOW η_{MECH}

INSTEAD USE: $bhp = 2\pi(\tau)(N)$ **REV IS DIMENSIONLESS**

$$= 2\pi(52.52\ FT\cdot LBf)\left(30{,}000\ \frac{REV}{MIN}\right)\left(\frac{1\ HP}{33{,}000\ FT\,LBf/MIN}\right)$$

$$\boxed{bhp = 300.0\ HP}$$

→ NOTICE $bhp < ihp$, THIS IS EXPECTED SINCE:

$$\boxed{\eta_{MECH} = \frac{bhp}{ihp} = \frac{(SMALLER)}{(BIGGER)} = 98.3\%}$$

(d) MECHANICAL LOSSES – THIS IS THE HP <u>NOT</u> TRANSFERRED TO THE LOAD

$$LOSS_{MECH} = ihp - bhp = 305.3 - 300.0$$

$$\boxed{LOSS_{MECH} = 5.3\ HP}$$

(e) AIR FUEL RATIO, AFR (NOTE: A RATIO IS DIMENSIONLESS)

$$AFR = \frac{\dot{m}_{AIR}}{\dot{m}_{FUEL}} \qquad (\text{NOTE: BOTH ARE GIVEN})$$

$$= \frac{4.08\ LBm/S\ (60\ S/MIN)}{4.87\ LBm/MIN}$$

$$\boxed{AFR = 50.27}$$

CONTINUE ANALYSIS:

(f) AIR RATE, AR $\left[\frac{LBm/HR}{HP}\right]$

$$AR = \frac{\dot{m}_{AIR}}{bhp} = \frac{4.08\ LBm/s\ (3600\ s/HR)}{300.0\ HP}$$

$$\boxed{AR = 48.96\ \frac{LBm/HR}{HP}}$$

NOTE: THIS IS THE RATE OF <u>AIR</u> THAT MUST BE COMPRESSED FOR 1 bhp

(g) BRAKE SPECIFIC FUEL CONSUMPTION (bsfc) $\left[\frac{LBm/HR}{HP}\right]$

$$bsfc = \frac{\dot{m}_{FUEL}}{bhp} = \frac{4.87\ LBm/MIN\ (60\ MIN/HR)}{300.0\ HP}$$

$$\boxed{bsfc = 0.974\ \frac{LBm/HR}{HP}}$$

NOTE: SIMILAR TO AR, THIS IS THE RATE OF <u>FUEL</u> CONSUMPTION FOR 1 bhp

(h) OVERALL EFFICIENCY, η_{OA} [%]

$$\eta_{OA} = \eta_{CC} \times \eta_{TH} \times \eta_{MECH}$$

$$= \frac{bhp}{\dot{m}_{FUEL}\,(LHV)}, \quad LHV \equiv \text{LOWER HEATING VALUE}\ \left[\frac{Btu}{LBm}\right]$$

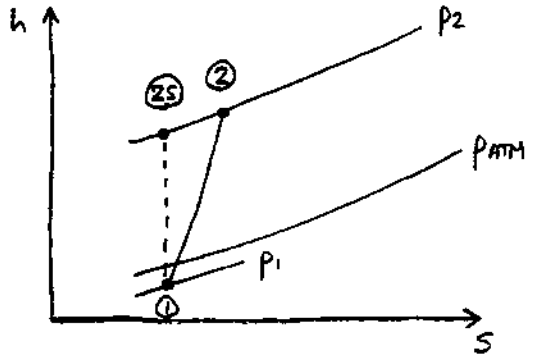
$$= \frac{300\,HP\ \left(42.42\ \frac{Btu/MIN}{HP}\right)}{4.87\ LBm/MIN\ (18{,}300\ Btu/LBm)}$$

$$\boxed{\eta_{OA} = 14.3\%}$$

NOTE: THIS IS HOW MUCH CHEMICAL ENERGY (OF THE FUEL) WAS CONVERTED TO MECHANICAL ENERGY (DELIVERED TO LOAD)

SOME THINGS THIS PROBLEM LEFT OUT:

① COMPRESSOR EFFICIENCY η_c [%]



FROM THE PROPERTY TABLE:

$h_1 = 126.7 \frac{Btu}{lbm}$

$h_{2s} = 211.6 \frac{Btu}{lbm}$

$h_2 = 232.8 \frac{Btu}{lbm}$

NOTE: $W_{1-2s} \rightarrow$ IDEAL
$W_{1-2} \rightarrow$ ACTUAL

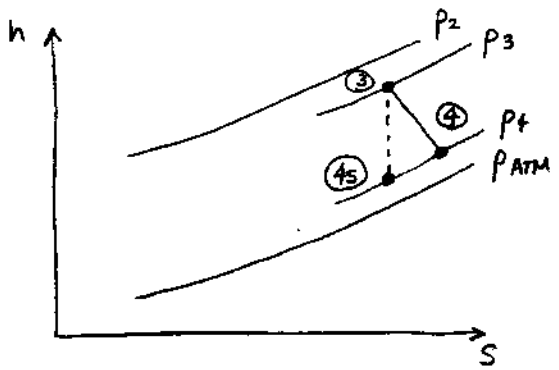
$$\eta_c = \frac{W_c\,(\text{IDEAL})}{W_c\,(\text{ACTUAL})} = \frac{(\text{SMALLER})}{(\text{BIGGER})}$$

$$= \frac{h_{2s} - h_1}{h_2 - h_1}$$

$$= \frac{211.6 - 126.7}{232.8 - 126.7}$$

$$\boxed{\eta_c = 80.0\%}$$

② TURBINE EFFICIENCY η_T [%]



FROM THE PROPERTY TABLES:

$h_3 = 560.3 \frac{Btu}{lbm}$

$h_{4s} = 373.1 \frac{Btu}{lbm}$

$h_4 = 401.3 \frac{Btu}{lbm}$

NOTE: $W_{3-4s} \rightarrow$ IDEAL
$W_{3-4} \rightarrow$ ACTUAL

$$\eta_T = \frac{W_T\,(\text{ACTUAL})}{W_T\,(\text{IDEAL})} = \frac{(\text{SMALLER})}{(\text{BIGGER})}$$

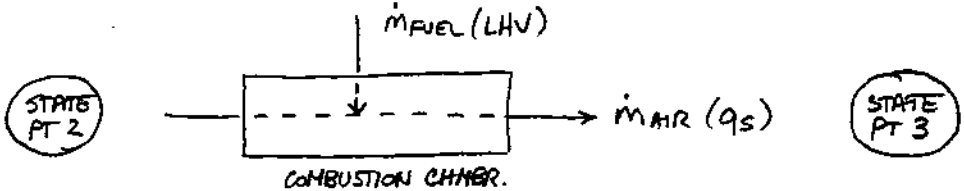
$$= \frac{h_3 - h_4}{h_3 - h_{4s}}$$

$$= \frac{560.3 - 401.3}{560.3 - 373.1}$$

$$\boxed{\eta_T = 84.9\%}$$

SOME THINGS THIS PROBLEM LEFT OUT: (CONT'D)

③ COMBUSTION CHAMBER EFFICIENCY, η_{cc} [%]



$$\left[\dot{m}_{FUEL}(LHV) = \dot{m}_{AIR}(q_s)\right] \rightarrow \text{ONLY WHEN } \eta_{cc} = 100\% \text{ (ie FULL COMBUSTION)}$$

- BETTER TO ALWAYS USE THIS:

$$\eta_{cc} = \frac{\dot{m}_{AIR}(q_s)}{\dot{m}_{FUEL}(LHV)}$$

$$q_s = q_{23} = h_3 - h_2 = 560.3 - 232.8$$

$$q_s = 327.5 \ \frac{Btu}{LBm}$$

$$= \frac{4.08 \frac{LBm}{s}\left(60 \frac{s}{MIN}\right)\left(327.5 \frac{Btu}{LBm}\right)}{4.87 \frac{LBm}{MIN}\left(18{,}300 \frac{Btu}{LBm}\right)}$$

$$\boxed{\eta_{cc} = 90.0\%}$$