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MET 350 Thermal Applications
Dr. Orlando Ayala
Spring 2017
Test 1

Take home – Due Sunday February 19th 2017 before midnight.

READ FIRST

1. RELAX!!!! DO NOT OVERTHINK THE PROBLEMS!!!! There is nothing hidden. The test was designed for you to pass and get the maximum number of points, while learning at the same time. HINT: THINK BEFORE TRYING TO USE/FIND EQUATIONS (OR EVEN FIND SIMILAR PROBLEMS)
2. The total points on this test are one hundred (100). Ten (10) points are from your HW assignments, and ten (10) other points are based on the basis of technical writing. The other eighty (80) points will come from the problem solutions. For the technical writing I will follow the attached rubric.
3. There are 3 problems and you will have to solve only 2 of them. Each worth (80/2) points. If solving more than 2, I will grade the first two problems you submit.
4. What you turn in should be only your own work. You cannot discuss the exam with anyone, except me. Call me, skype me, text me, email me, come to my office, if you have any question.
5. I do not read minds. You should be explicit and organized in your answers. Use drawings/figures. If you make a mistake, do not erase it. Rather use that opportunity to explain why you think it is a mistake and show the way to correct the problem.
6. You have to turn in your test ON TIME and ONLY through BLACKBOARD. You must submit only one file and it has to be a pdf file. For the ePortfolio you are also supposed to upload this artifact to your Google drive. When you are done solving the test, please go ahead and upload it now before you forget.
7. Do not start at the last minute so you can handle anything that could happen. Late tests will not be accepted. Test submitted through email will not be accepted either.
8. Cheating is completely wrong. The ODU Student Honor Pledge reads: "I pledge to support the honor system of Old Dominion University. I will refrain from any form of academic dishonesty or deception, such as cheating or plagiarism." By attending Old Dominion University you have accepted the responsibility to abide by this code. This is an institutional policy approved by the Board of Visitors. It is important to remind you the following part of the Honor Code:

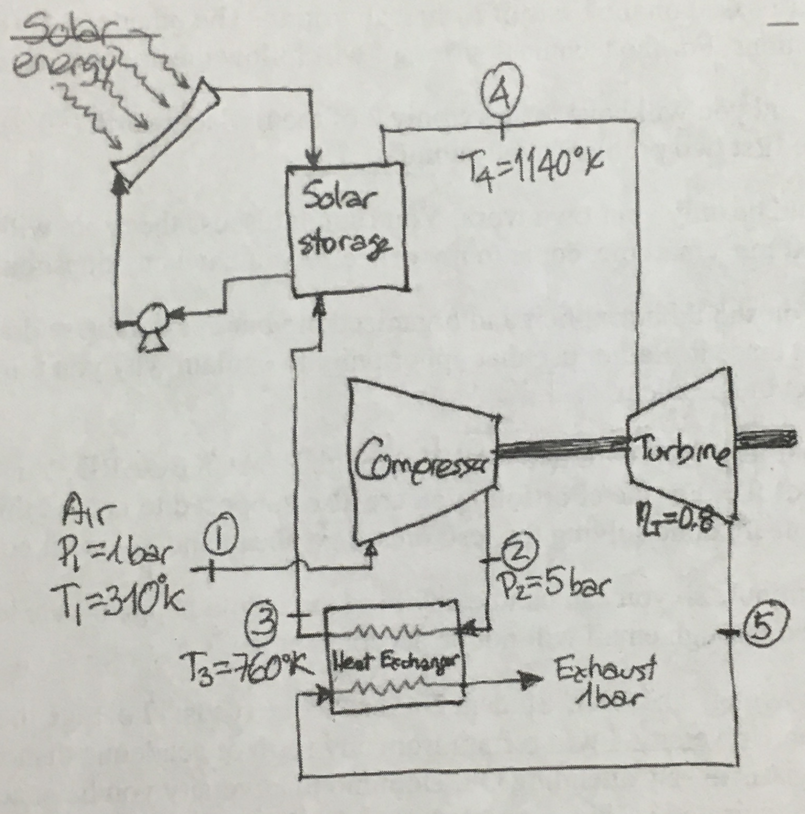
> IX. PROHIBITED CONDUCT
> A. Academic Integrity violations, including:
> 1. *Cheating*: Using unauthorized assistance, materials, study aids, or other information in any academic exercise (Examples of cheating include, but are not limited to, the following: using unapproved resources or assistance to complete an assignment, paper, project, quiz or exam; collaborating in violation of a faculty member's instructions; and submitting the same, or substantially the same, paper to more than one course for academic credit without first obtaining the approval of faculty).

With that said, you are NOT authorized to use any online source of any type, unless is ODU related.

1. Air at 95 kPa, 290 K gets into an ideal cold air-standard Diesel cycle (before compression). The compression ratio is 20. For a thermal efficiency of 60%, what would be the maximum temperature in the cycle? HINT: You can solve this problem the way you know by using a trial and error process, i.e., assume values of the maximum temperature until you get the desired thermal efficiency.

2. Solar energy has been proposed as the source of heat addition in an ideal cold air-standard Brayton cycle, as shown in the figure. With the operating data provided in the figure, determine:

(a) the thermal efficiency and the heat exchanger effectiveness.
(b) the air mass flow rate, in kg/s, for a net power output of 500 kW.
(c) what would be the thermal efficiency if the heat exchanger were operating at 100% effectiveness?



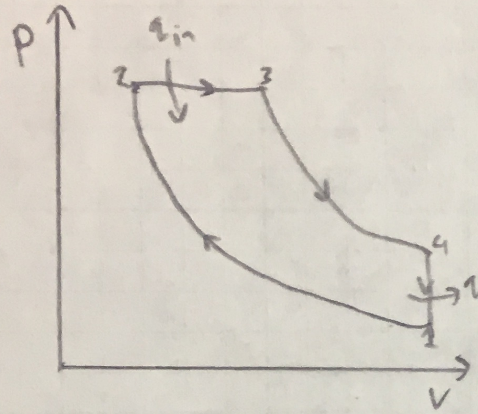
3. A turbojet aircraft flies with a velocity of 900 km/h at an altitude where the air temperature and pressure are -35 °C and 40 kPa. The combustion gases enter the turbine at 950 °C. The turbine produces 500 kJ/kg of work, all of which is used to drive the compressor. Assuming an isentropic efficiency of 80% for the compressor, an isentropic efficiency of 90% for the turbine, and using variable specific heats, determine:

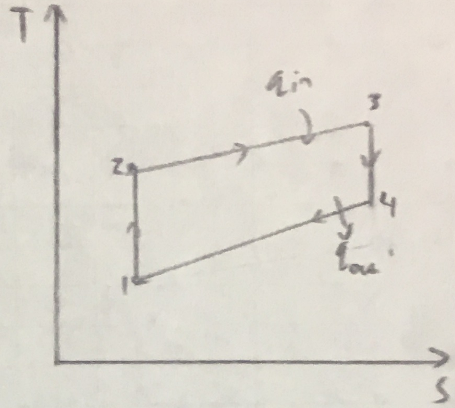
(a) the pressure of combustion gases at the turbine exit,
(b) the velocity of the gases at the nozzle exit, and
(c) the thrust for this engine if the diffuser inlet diameter is 1.6 m.

①

Purpose: Find the max temperature in the ideal cold air standard Diesel cycle (before compression).

Drawings and Diagrams:





Sources: - Cengel and boles. Thermodynamics an Engineering Approach 8th edition. 2015
- Blackboard nots, Unit one

Design considerations:

To Solve this problem, I assume the following:

1) Air behaves as an ideal gas. $R = .287 \frac{kJ}{kg\,K}$
2) Isentropic compression and expansion process.
3) constant pressure combustion, constant volume
4) Exhaust and intake as heat removal process
5) Kinetic and potential energy are negligible.

Data and variables:

$T_1 = 290K$ $\qquad r = 20 = \frac{V_1}{V_2}$

$P_1 = 95kPa$

$\eta_{TH} = .60$

Materials:

Air as ideal gas

Procedure and Calculations:

1) trial and error process, where you plug in values for temperature (T) until you get desired thermal efficiency ($\eta = .60$). Seen as

T	$\eta = .60$
?K	.60
?K	.60

2) Obtain all states.

(1) → isentropic → (2) → P constant → (3) → isentropic → (4) V constant

State 1:

$P_1 = 95 kPa$

$T_1 = 290 K$

$V_1 = \frac{RT_1}{P_1}$

$= \frac{(.287 \frac{kJ}{kgK})(290K)}{95 kPa}$

$V_1 = .8761 \frac{m^3}{kg}$

State 2 (compression ratio):

$\frac{V_1}{V_2} = 20 = r$

$V_2 = \frac{V_1}{r} = \frac{.8761 \frac{m^3}{kg}}{20}$

$V_2 = .0438 \frac{m^3}{kg}$

isentropic compression:

$\frac{T_2}{T_1} = \left(\frac{V_2}{V_1}\right)^{k-1}$

$\frac{T_2}{290K} = 20^{1.4-1}$

$T_2 = 961.2K$

$P_2 = \frac{RT_2}{V_2} = \frac{(.287 \frac{kJ}{kgK})(961.2K)}{.0438 \frac{m^3}{kg}}$

$P_2 = 6298 kPa$

State 3:

$P_2 = P_3$

State 4:

$V_4 = V_1$

isentropic expansion

$\frac{T_4}{T_3} = \left(\frac{V_4}{V_3}\right)^{k-1}$

- From TS diagram we see T_3 has the highest temperature in this Diesel Cycle. Lets use $T_3 = 3040K$, we know its going to be higher than $T_2 = 961.2K$ - Now Solve for T_4 with our T_3

If $T_3 = 3040K$

$\frac{V_3}{V_2} = \frac{T_2}{T_3}$

$\frac{V_3}{V_2} = \frac{961.19}{3040} = .316$

$\left(\frac{V_3}{V_2} \cdot \frac{V_2}{V_4}\right)^{k-1} = \frac{T_4}{T_3}$

$\left(\frac{1}{.316} \cdot \frac{1}{20}\right)^{.4} \cdot 3040 = T_4$

$T_4 = 1454.1K$

- We have (n) thermal efficiency, therefore if T_3 is 3040 K and $T_4 = 1454.1$ we should get $n = .60$

$$n = .60 = 1 - \frac{1}{k}\left(\frac{T_4 - T_1}{T_3 - T_2}\right)$$

$$.60 = 1 - \frac{1}{1.4}\left(\frac{1454.1 - 290}{3040 - 961.19}\right)$$

$$.60 = 1 - .39997$$

$$.60 = .60003 \checkmark$$

Our temp max is $T_3 = 3040K$

Summary: Here are the known states of this Diesel Cycle after results

→ (1) —Isentropic→ (2) —P constant→ (3) —Isentropic→ (4) —V constant→

(1): $P_1 = 95$ kPa, $T_1 = 290$ K

(2): $P_2 = 6296$ kPa, $T_2 = 961.2$ K

(3): $P_3 = 6296$ kPa, $T_3 = 3040$ K

(4): $T_4 = 1454.1$ K, $V_4 = V_1$

$$P_4 = \frac{R T_4}{V_4}$$

$$P_4 = \frac{(.287\ \mathrm{kJ/kg\,k})(1454.1\mathrm{K})}{.8761\ \frac{m^3}{kg}}$$

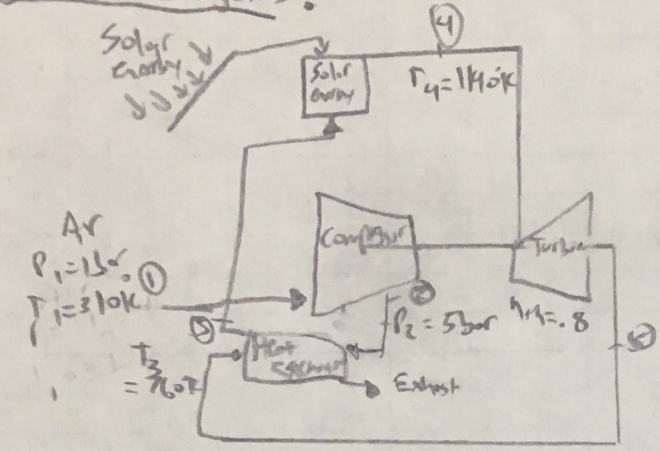
$$P_4 = 476.34\ \mathrm{kPa}$$

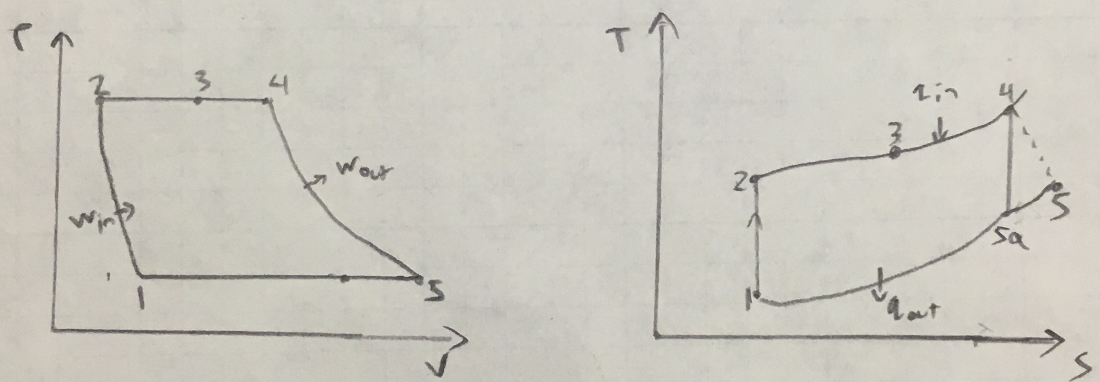
Analysis:

- After trial and error of finding the correct T_3 that would give you a $n = .6$ we figured out $T_3 = 3040$ K. It checks out on the T-S diagram and if we plug in the numbers we get desired efficiency of 60%. Another way to solve this is to obtain states then for states 3 and 4 you would have a T_3 left over. Then solve for T_3 by quadratic formula.

Purpose: Determine thermal efficiency and heat exchanger effectiveness. Find the air mass flow rate and what the thermal efficiency would be if the heat exchanger were operating at 80 % effectiveness. In the solar powered ideal cold air-standard Brayton cycle.

Drawings and Diagrams:





Sources: Cengel and Boles Thermodynamics an Engineering approach 8th edition McGraw Hill. 2015
- Blackboard notes, Unit One

Design Considerations: I assume the following
1) Air behaves as an ideal gas $R = .287 \frac{kJ}{kg\,K}$
2) No heat loss in connecting pipes, neither fluid flow friction losses
3) isentropic expansion and compression
4) Kinetic and potential energy are negligible.

Data and variables:

$T_1 = 310K$ $P_2 = 5bar$ $T_3 = 760K$ $T_4 = 1140K$

$P_1 = 1bar$ $\approx 500kPa$

$\approx 100kPa$

$\eta_{th} = .8$

Ideal gas properties of Air table

$T_1 = 310K$ $T_2 = 491K$ $T_3 = 760K$ $T_4 = 1140K$

$h_1 = 310.24 kJ/kg$ $h_2 = 492.74 kJ/kg$ $h_3 = 778.16 kJ/kg$ $h_4 = 1207.57 kJ/kg$

$P_r = 193.1$

materials: -Air as ideal gas

-solar energy

Procedure and Calculations - For part a, we need to obtain all the states.

→ (1) —Isentropic→ (2) —P constant→ (3) —constant→ (4) —isentropic→ (5) —P constant→

(1): $T_1 = 310K$, $P_1 = 100kPa$

(2): $P_2 = 500kPa$

(3): $T_3 = 760K$, $P_2 = P_3$

(4): $T_4 = 1140K$, $P_4 = P_3$

(5), (5a): $P_5 = P_1$

isentropic compression

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$$T_2 = \left(\frac{500kPa}{100kPa}\right)^{\frac{1.4-1}{1.4}} \cdot 310K$$

$$T_2 = 491K$$

isentropic expansion

$$\frac{P_4}{P_5} = \frac{P_{r4}}{P_{r5a}}$$

$$\frac{1}{5} \cdot 193.1 = P_{r5a}$$

$$P_{r5a} = 38.62$$

Properties of air table

$$h_{5a} = 767.29 + (778.16 - 767.29)\left(\frac{38.62 - 37.35}{39.27 - 37.35}\right)$$

$$h_{5a} = 774.493 kJ/kg$$

$$\eta_t = \frac{h_4 - h_5}{h_4 - h_{5a}}$$

$$.8 = \frac{1207.57 - h_5}{1207.57 - 774.493}$$

$$h_5 = 861.1 kJ/kg$$

$$\frac{T_4}{T_{5a}} = \left(\frac{P_4}{P_{5a}}\right)^{\frac{k-1}{k}}$$

$$T_{5a} = \left(\frac{500kPa}{100kPa}\right)^{\frac{1.4-1}{1.4}} \div 1140K$$

$$T_{5a} = 719.4 K$$

$$\eta_t = \frac{T_4 - T_5}{T_4 - T_{5a}}$$

$$.8 = \frac{1140 - T_5}{1140 - 719.4}$$

$$T_5 = 804 K$$

- Now that we have all our states we can solve the problems.

- Using equation sheet on black board

a) Thermal efficiency

$$\eta_{thermal} = \frac{W_{net}}{Q_{in}} = \frac{(h_4 - h_5) - (h_2 - h_1)}{h_4 - h_3}$$

$$= \frac{(1207.57 - 861.1) - (492.74 - 310.24)}{(1207.57 - 778.18)} = \frac{346.47 - 182.5}{429.39}$$

$$= \frac{163.97 \text{ kJ/kg}}{429.39 \text{ kJ/kg}}$$

$$= .3818$$

$$\eta_{thermal} = 38.2\%$$

Heat exchanger effectiveness

$$\eta_{effectiveness} = \frac{T_3 - T_2}{T_5 - T_2} = \frac{760 - 491}{804 - 491}$$

$$= \frac{269}{313} = .8594$$

$$\text{effectiveness} = 85.94\%$$

b) $\dot{W}_{net} = \dot{m}(w_{net})$

$$500\text{kW} = \dot{m}[(h_4 - h_5) - (h_2 - h_1)]$$

$$500\text{kW} = \dot{m}[(1207.57 - 861.1) - (492.74 - 310.24)]$$

$$500\text{kW} = \dot{m}(163.97 \text{ kJ/kg})$$

$$\dot{m} = 3.049 \text{ kg/s}$$

c) $\eta_{thermal} = ?$ if efficiency $= 100\%$

$$1 = \frac{T_3 - T_2}{T_5 - T_2}$$

$$\eta_{thermal} = \frac{W_{net}}{Q_{in}} = \frac{c_p(T_4 - T_3 - T_2 + T_1)}{c_p(T_4 - T_3)} = \frac{1140 - 804 - 491 + 310}{1140 - 760} = \frac{155}{380} = .40789$$

$$\eta_{th} = 40.78\%$$

Summary:

Here are values of all states and table results.

→ (1) —isentropic→ (2) —P constant→ (3) —P constant→ (4) —isentropic→ (5) (5a) —P constant→

$T_1 = 310K$
$P_1 = 100kPa$

$T_2 = 491K$
$P_2 = 500kPa$

$T_3 = 760K$
$P_3 = 500kPa$

$T_4 = 1140K$
$P_4 = 500kPa$

$T_5 = 804K$
$T_{5a} = 719.4K$
$P_5 = 100kPa$

- $\eta_{thermal} = 38.2\%$
- Heat exchanger effectiveness = 85.94%
- $\dot{m} = 3.049$ kg/s for 500kW net power output
- $\eta_{thermal} = 40.78\%$ for 100% heat exchanger effectiveness.

Analysis:

Solar energy is a good power source that we need especially in the future so we don't have to rely on fossil fuels. We obtained a thermal efficiency of 38.2% and a heat exchanger effect of 85.94%. But when we increased the heat exchanger effectiveness to 100% we got a thermal efficiency of 40.76% which was to be expected if you increase effectiveness. We also solved for a air mass flow rate of 3.049 kg/s with a 500kW net power. In the future this system would need a solution for power when the sun sets.

(3)

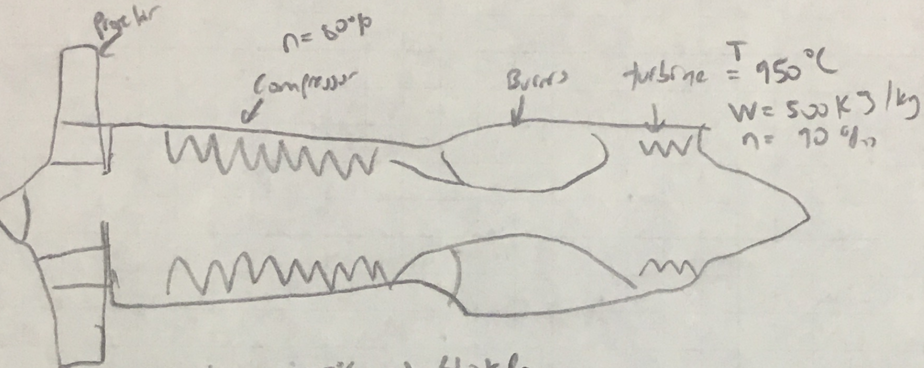
Purpose: Determine the following in a jet propulsion cycle.

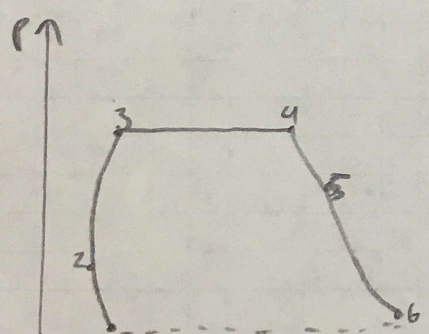
a) the pressure of combustion gases at the exit,

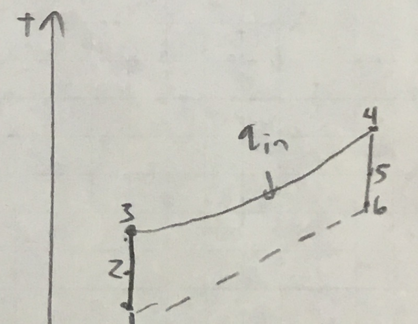
b) the velocity of the gases at the nozzle exit,

c) the thrust for this engine if the diffuser inlet diameter is 1.6m.

Drawings and Diagrams:







Sources: Cengel and Boles. Thermodynamics an engineering approach. 6th edition. McGraw Hill 2015

- blackboard notes, unit one

Design Considerations!

- Ideal operation = $C_p = 1.00493 \frac{KJ}{Kg \cdot K}$, $C_v = .0717926 \frac{kJ}{Kg \cdot K}$, $k = 1.3998$
- Turbojet aircraft V = 900 km/h
- net work output of a jet propulsion cycle is zero
- The turbine work input is equal to compressor work output.
- Kinetic and potential energy are negligible, except at diffuser inlet and nozzle exit.

Data and Variables:

$V = 900$ km/h
$P = 40$ kPa
$T = -35$°C

$T_{turbine\ inlet} = 950$°C

$q_{turbine} = 500$ kJ/kg

$\eta_{comp} = 80\%$

$\eta_{turbine} = 90\%$

$h_{3s} = 500$ kJ/kg

materials: - Air as an ideal gas

Procedure and Calculations:

- Solve for all States 1-6
- After getting all the states we can start solving problems.
- We can get states 1-2 with given information and isentropic equations.
- After use h_{3s} to get h_3 than T_3 and we can Solve for all states after.

- a) use P_5 as the pressure of combustion gases at turbine exit.

- b) For velocity of gases we $V_6 = \sqrt{2c_p(T_5 - T_6)}$

- c) For thrust with an diffuser inlet diameter of 1.6m we use the equation $F = \dot{m}(V_{exit} - V_{inlet})$

Procedure and Calculations:

→ (1) —Isentropic Diffuser→ (2) —Isentropic→ (3) —P constant→ (4) —Isentropic→ (5) —Isentropic→ (6) →

State 1

$P_1 = 40 kPa$

$T_1 = 238.15 K$

$v_1 = \frac{RT_1}{P_1} = \frac{(287 \frac{kJ}{kgK})(238.15K)}{40 kPa}$

$v_1 = 1.708 m^3/kg$

$V_1 = 250 m/s$

1st law to process 1-2

$\frac{V_1^2}{2} + h_1 = \frac{V_2^2}{2} + h_2$

$\frac{V_1^2}{2} = cp(T_2 - T_1)$

$T_2 = T_1 + \frac{V_1^2}{2cp}$

$T_2 = 238.15K + \frac{(250 m/s)^2}{(2 \cdot 1000)}$

$T_2 = 269.4 K$

Isentropic process

$\frac{P_2}{P_1} = \frac{T_2}{T_1}^{(\frac{k}{k-1})}$

$P_2 = \left(\frac{269.4K}{238.15K}\right)^{3.5} \cdot 40 kPa$

$P_2 = 61.58 kPa$

State 2

$V_2 = 0 m/s$

$T_2 = 269.4 K$

$P_2 = 61.58 kPa$

$h_2 = 270.11 kJ/kg$

State 3

$P_3 = P_4$

$h_{3s} = 500 kJ/kg$

$\eta_{comp} = \frac{h_{3s} - h_2}{h_3 - h_2}$

$.80 = \frac{500 - 270.11}{h_3 - 270.11}$

$h_3 = 557.4 kJ/kg$

$T_3 = 550 K$ from ideal-gas table properties of air

Isentropic process

$\frac{P_3}{P_2} = \left(\frac{T_{3s}}{T_2}\right)^{\frac{k}{k-1}}$

$P_3 = \left(\frac{550K}{269.4K}\right)^{3.5} 61.58 kPa$

$P_3 = 748.7 kPa$

State 4

$T_4 = 1223.15 K$

$P_4 = P_3$

$P_4 = 748.7 kPa$

State 5

$V_5 = 0 m/s$

Since $w_c = w_t$

$h_3 - h_2 = h_4 - h_5$

$c_p(T_3 - T_2) = c_p(T_4 - T_5)$

$T_5 = T_4 - (T_3 - T_2)$

$T_5 = 1223.15K - (550K - 269.4K)$

$T_5 = 942.55K$

Isentropic process

$\frac{P_5}{P_4} = \left(\frac{T_5}{T_4}\right)^{k/k-1}$

$P_5 = \left(\frac{942.55}{1223.15K}\right)^{3.5} \cdot 748.7$

$P_5 = 300.7 kPa$

Isentropic process

$\frac{T_6}{T_5} = \left(\frac{P_6}{P_5}\right)^{\frac{k-1}{k}}$

$T_6 = \left(\frac{40}{300.7}\right)^{.286} 942.55$

$T_6 = 529.35 K$

State 6

$P_6 = P_1$

$P_6 = 40 kPa$

$T_6 = 529.35K$

a) The pressure of combustion gases at turbine exit is equal to P_5 which is 300.7 kPa.

b) $V_{exhaust\ gases} = V_6$

Apply 1st law to process 5-6:

$$\frac{V_5^2}{V_2} + h_5 = \frac{V_6^2}{2} + h_6$$

$$\frac{V_6^2}{2} = c_p(T_5 - T_6)$$

$$V_6 = \sqrt{2c_p(442.55\ K - 529.35\ K)}$$

$$V_6 = 828.5\ m/s$$

c) Thrust for the engine if the diffuser with inlet diameter 1.6 m.

$$F = \dot{m}(V_{exit} - V_{inlet})$$

$$= \dot{m}(V_6 - V_1)$$

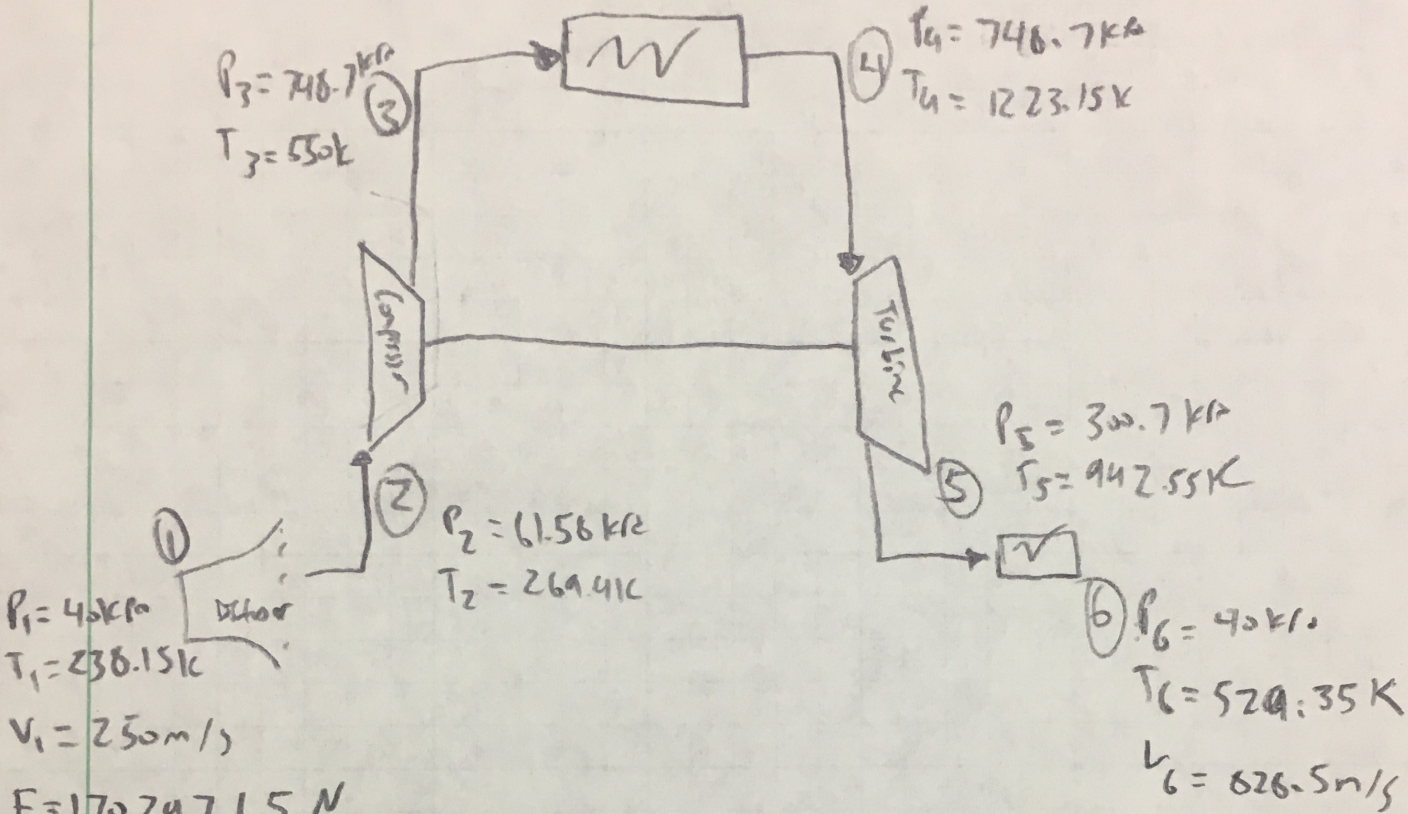
$$= \rho_1 V_1 A_1 (V_6 - V_1)$$

$$= \frac{V_1}{v_1} \cdot \frac{\pi}{4} D^2 (V_6 - V_1)$$

$$= \left(\frac{250\ m/s}{1.708\ m^3/kg}\right) \frac{\pi}{4} 1.6^2 (828.5\ m/s - 250\ m/s)$$

$$F = 170{,}247.65\ N$$

Summary: Here is a Schematic of a turbojet



Analysis:

After solving the problem we see that from a) the turbine provides enough power to drive the compressor and $W_{turbine} = W_{compr}$. The pressure at the exit is 300.7 kPa. b) the nozzle accelerates to a high velocity so air can be propelled out the jet at a 826.5 m/s velocity. c) The point of the turbojet is to produce thrust so it can move forward and our thrust for this jet is 170,247.6N.