Name: ____.

MET 350 Thermal Applications
Dr. Orlando Ayala
Spring 2024
Test 1

Take home – Due Sunday February 18th 2024 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 2 problems. Each problem will be worth (80/2) points.
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 (which is optional) you are supposed to upload this artifact to your Google drive. I will provide more instructions later.
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) Calculate the effectiveness of the regeneration heat exchanger from problem 9-133 we discussed in class (this is not problem 9-133 from the book!). Compare the value of the effectiveness against the typical values of effectiveness show in the figure. Keep in mind that when designing a HX the designer tries to reach the maximum effectiveness for a fixed C_{min}/C_{max}.

At full load the engine produces 800 kW of power. For this engine to service a partial load, the heat addition in both or one of the combustion chambers is reduced. When such changes take place the regenerator effectiveness remains constant. Please note that modifications to the flow route might occur as required.

What is the produced power if the reheater is turned off? Does the thermal efficiency change? Why?

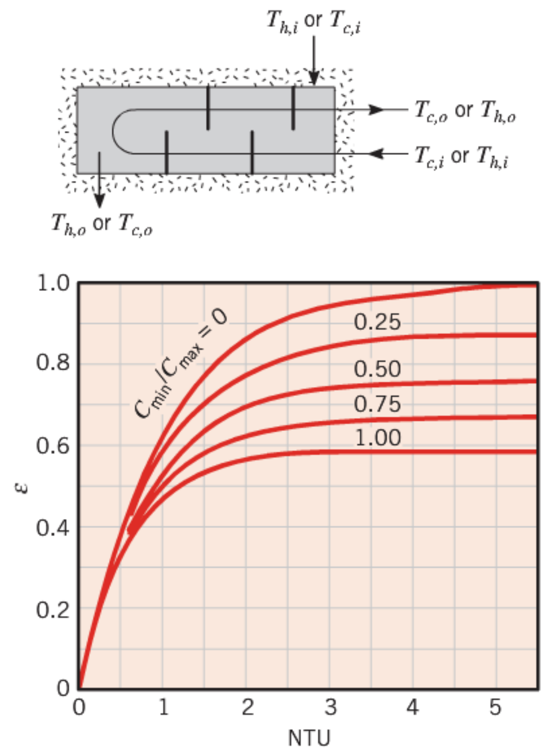


FIGURE 11.12 Effectiveness of a shell-and-tube heat exchanger with one shell and any multiple of two tube passes (two, four, etc.,

2) Calculate the propulsive efficiency of the jet propulsion cycle we solved in class, problem 9-142 (this is not problem 9-142 from the book!).

Repeat the problem using a compressor efficiency of 80 percent and a turbine efficiecny of 85 percent. Use Cp and Cv variable. Provide the pressure and temperature of ALL the states (including the actual states leaving the compressor and the turbine). Calculate the propulsive efficiency of the jet propulsion cycle and compare to the previous one. Does the propulsion efficiency change? Why?

Problem solution rubric

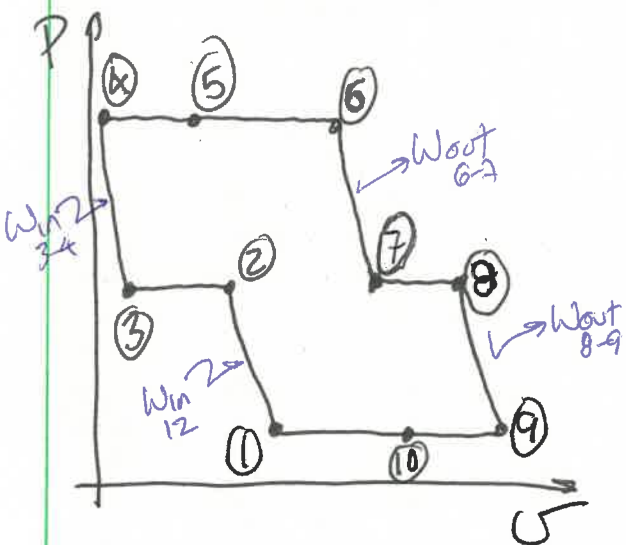
	Exceeds Standard	Meets Standard	Approaches Standard	Needs Attention
	4	3	2	1
	10 points	7 points	4 points	0 points
1. Purpose 5%	The purpose of the section to be answered is clearly identified and stated.	The purpose of the section to be answered is identified, but is stated in a somewhat unclear manner.	The purpose of the section to be answered is partially identified, and is stated in a somewhat unclear manner.	The purpose of the section to be answered is erroneous or irrelevant.
2. Drawings & Diagrams 10%	Clear and accurate diagrams are included and make the section easier to understand. Diagrams are labeled neatly and accurately.	Diagrams are included and are labeled neatly and accurately.	Diagrams are included and are labeled.	Needed diagrams are missing OR are missing important labels.
3. Sources 5%	Several reputable background sources were used and cited correctly.	A few reputable background sources are used and cited correctly.	A few background sources are used and cited correctly, but some are not reputable sources.	Background sources are cited incorrectly.
4. Design considerations (assumptions, safety, cost, etc) 10%	Design is carried out with applicable assumptions and full attention to safety and cost, etc.	Design is generally carried out with assumptions and attention to safety, cost, etc.	Design is carried out with some assumptions and some attention to safety, cost, etc.	Assumptions, safety and cost were ignored in the design.
5. Data and variables 5%	All data and variables are clearly described with all relevant details.	All data and variables are clearly described with most relevant details.	Most data and variables are clearly described with most relevant details.	Data and variables are not described OR the majority lack sufficient detail.
6. Procedure 25%	Procedure is described in clear steps. The step description is in a complete and easy to understand short paragraph.	Procedure is described in clear steps but the step description is not in a complete short paragraph.	Procedure is described in clear steps. The step description is in a complete short paragraph but it is difficult to understand.	Procedure is not described in clear steps at all.
7. Calculations 20%	All calculations are shown and the results are correct and labeled appropriately. The units of all values are shown.	Some calculations are shown and the results are correct and labeled appropriately.	Some calculations are shown and the results labeled appropriately.	No calculations are shown OR results are inaccurate or mislabeled.
8. Summary 5%	Summary describes the design, the relevant information and some future implications.	Summary describes the design and some relevant information.	Summary describes the design.	No summary is written.
9. Materials 5%	All materials used in the design are clearly and accurately described.	Almost all materials used in the design are clearly and accurately described.	Most of the materials used in the design are clearly and accurately described.	Many materials are described inaccurately OR are not described at all.
10. Analysis 10%	The design is discussed and analyzed. Argumentative predictions are made about what might happen in case of change in the operation and how the design could be change.	The design is discussed and analyzed. Argumentative predictions are made about what might happen in case of change in the operation.	The design is discussed and analyzed. No argumentative predictions are made about what might happen in case of change in the operation and how the design could be change.	The design is not discussed and analyzed.

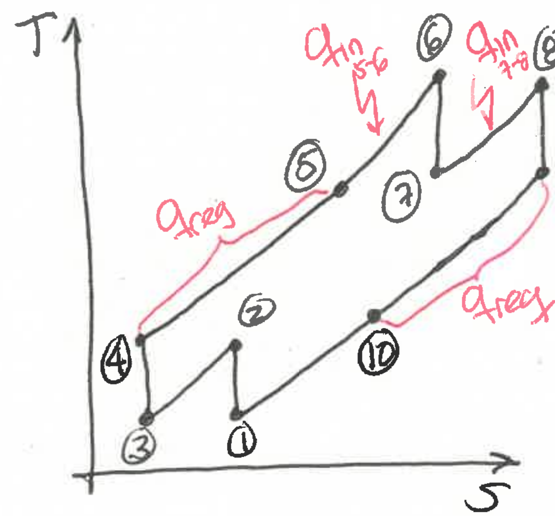
① PURPOSE [A]

Calculate the heat exchanger effectivenes in a Rankine cycle with reheater, cooling, and regeneration

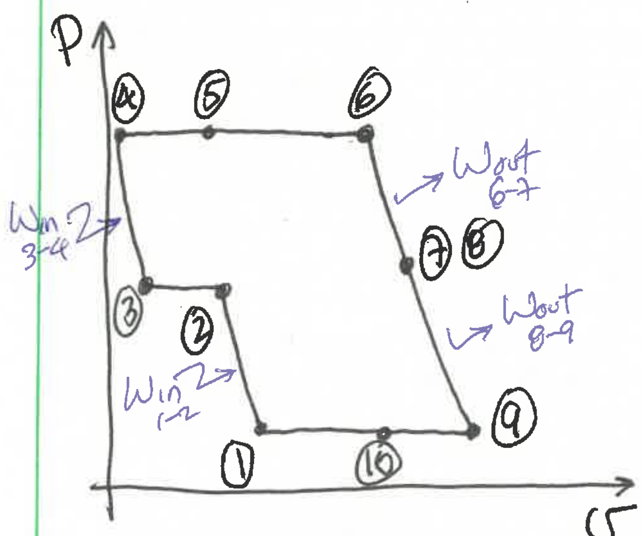
Calculate the thermal efficiency of the same cycle if the reheater is turned off. Also compute the power.

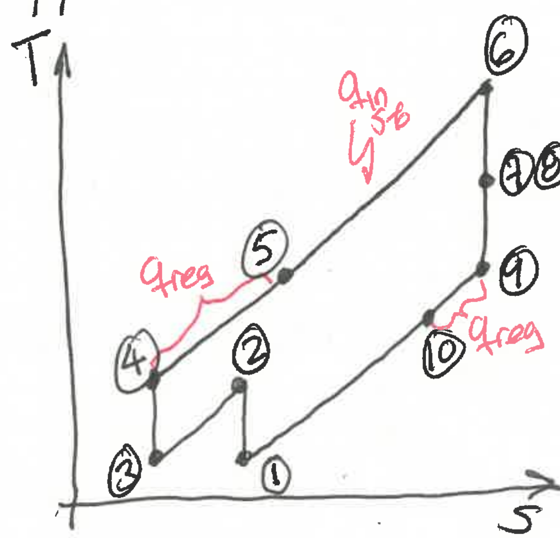
DRAWINGS & DIAGRAMS





When the reheater is off:





SOURCES

B

Cengel & Boles. "Thermodynamics – An Engineering Approach" 8th edition, McGraw Hill. 2015

DESIGN CONSIDERATIONS

I assume the following

1) Air behaves as ideal gas ($R = 0.287 \frac{kJ}{kg \cdot K}$)
2) Cp & Cv are constant & evaluated at 25°C (cold-air assumption)
3) Isentropic compression & expansion
4) Constant pressure heat addition & heat rejection.
5) $C_p = 1.004926 \frac{kJ}{kg \cdot K}$, $C_v = 0.717926 \frac{kJ}{kg \cdot K}$, $k = \frac{C_p}{C_v} = 1.399763$
6) HX effectiveness remains constant

DATA & VARIABLES

* T = 17°C, P = 100 kPa at air inlet
* $r_p = 14$ at each compression stage
* 300 kJ/kg of heat added in each combustion chamber.
* Reheater is turned off

PROCEDURE & CALCULATIONS

The HX effectiveness is:

$$\varepsilon = \frac{h_5 - h_4}{h_9 - h_4} = \frac{C_p(T_5 - T_4)}{C_p(T_9 - T_4)} = \frac{T_5 - T_4}{T_9 - T_4}$$

$$\varepsilon = \frac{451.08K - 431.08K}{540.51K - 431.08K}$$

$$\boxed{\varepsilon = 18.276\%}$$

Using temperatures from the solution from class

Let us get states when reheater is turned off:

→ ① —Isent→ ② —Pcond→ ③ —Isent→ ④ —Pconst (Regenerator)→ ⑤ —Pconst, q_{in}→ ⑥ —Isent→ ⑦ —NOTHING→ ⑧ —Isent→ ⑨ —Pconst (Regenerator)→ ⑩ —Pconst→

①	$P_1 = 100\,kPa$, $T_1 = 290.15\,K$, $v_1 = 0.833\,\frac{m^3}{kg}$
②	$P_2 = 400\,kPa$, $T_2 = 431.16\,K$, $v_2 = 0.31\,\frac{m^3}{kg}$
③	$P_3 = 400\,kPa$, $T_3 = 290.15\,K$, $v_3 = 0.21\,m^3/kg$
④	$P_4 = 1{,}600\,kPa$, $T_4 = 431.08\,K$, $v_4 = 0.077\,\frac{m^3}{kg}$
⑤	$P_5 = 1{,}600\,kPa$
⑥	$P_6 = 1{,}600\,kPa$
⑦	$P_7 = 400\,kPa$
⑧	SAME AS ⑦
⑨	$P_9 = 100\,kPa$
⑩	$P_{10} = 100\,kPa$

(States ① – ④:) Same as in the original problem

The pressures for all states remain the same as in the original problem. The temperatures DO change. We know the effectiveness is constant and equal to 18.276%, So, from

$$\varepsilon = \frac{T_5 - T_4}{T_9 - T_4}$$

we get:

$$T_5 = \varepsilon (T_9 - T_4) + T_4$$

The problem is that we do not know T_9. We need to find equations to get it

⑨ is related to ⑦: $T_9 = T_7 \left(\frac{P_9}{P_7}\right)^{\frac{k-1}{k}}$ (I)

⑦ is related to ⑥: $T_7 = T_6 \left(\frac{P_7}{P_6}\right)^{\frac{k-1}{k}}$ (II)

⑥ is related to ⑤: $T_6 = T_5 + \frac{q_{in}}{c_p}$ (III)

Plugging (III) into (II) and then (II) into (I):

$$T_9 = \left(T_5 + \frac{q_{in}}{c_p}\right)\left(\frac{P_7}{P_6}\right)^{\frac{k-1}{k}}\left(\frac{P_9}{P_7}\right)^{\frac{k-1}{k}}$$

Or,

$$T_9 = \left(T_5 + \frac{q_{in}}{c_p}\right)\left(\frac{P_9}{P_6}\right)^{\frac{k-1}{k}}$$

C

D

Plugging this equation into the one from effectiveness:

$$T_5 = \varepsilon\left[\left(T_5 + \frac{q_{in}}{c_p}\right)\left(\frac{P_9}{P_6}\right)^{\frac{k-1}{k}} - T_4\right] + T_4$$

Solving for T_5:

$$T_5 = \frac{\varepsilon \frac{q_{in}}{c_p}\left(\frac{P_9}{P_6}\right)^{\frac{k-1}{k}} + (1-\varepsilon)T_4}{\left[1 - \varepsilon\left(\frac{P_9}{P_6}\right)^{\frac{k-1}{k}}\right]}$$

Plugging numbers:

$$T_5 = \frac{0.18276 \times \frac{300\ kJ/kg}{1.004926\ \frac{kJ}{kg\cdot K}} \times \left(\frac{100\ kPa}{1{,}600\ kPa}\right)^{\frac{0.399763}{1.399763}} + (1-0.18276)\times 431.08\ K}{\left[1 - 0.18276\left(\frac{100\ kPa}{1{,}600\ kPa}\right)^{\frac{0.399763}{1.399763}}\right]}$$

$$= \frac{24.716\ K + 352.296\ K}{0.9172}$$

$$\boxed{T_5 = 411.047\ K}$$

Please note that this T_5 is lower than T_4!!

If this is happening is because T_9 is lower than T_4. Thus, the regenerator is heating up the exhaust gases! We are losing energy! The regenerator must be turned off as well by rerouting the working fluid.

Now the states have to be reworked:

① $\xrightarrow{\text{Isent}}$ ② $\xrightarrow{\text{Pconst}}$ ③ $\xrightarrow{\text{Isent}}$ ④ $\xrightarrow{\text{NOTHING}}$ ⑤ $\xrightarrow{\text{Pconst},\ q_{in}}$ ⑥ $\xrightarrow{\text{Isent}}$ ⑦ $\xrightarrow{\text{NOTHING}}$ ⑧ $\xrightarrow{\text{Isent}}$ ⑨ $\xrightarrow{\text{NOTHING}}$ ⑩

① $P_1 = 100\,kPa$, $T_1 = 290.15\,K$

② $P_2 = 400\,kPa$, $T_2 = 431.16\,K$

③ $P_3 = 400\,kPa$, $T_3 = 290.15\,K$

④ $P_4 = 1{,}600\,kPa$, $T_4 = 431.08\,K$

(States ① to ④: SAME AS BEFORE)

⑤ SAME AS ④

⑥ $P_6 = 1{,}600\,kPa$

⑦ $P_7 = 400\,kPa$

⑧ SAME AS ⑦

⑨ $P_9 = 100\,kPa$

⑩ SAME AS ⑩

$$T_6 = T_4 + \frac{q_{in}}{c_p}$$

$$T_6 = 729.609\,K$$

$$T_7 = T_6\left(\frac{P_7}{P_6}\right)^{\frac{k-1}{k}}$$

$$T_7 = 491.073\,K$$

$$T_9 = T_7\left(\frac{P_9}{P_7}\right)^{\frac{k-1}{k}}$$

$$T_9 = 330.523\,K$$

Note that T_9 is lower than T_4!! We should NOT use regenerator!

For the thermal efficiency:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{out_{6-7}} + w_{out_{8-9}} - w_{in_{1-2}} - w_{in_{3-4}}}{q_{in}} = \frac{c_p(T_6 - T_7) + c_p(T_8 - T_9) - c_p(T_2 - T_1) - c_p(T_4 - T_3)}{q_{in}}$$

$$\eta_{th} = \frac{116.327\ kJ/kg}{300.00\ kJ/kg}$$

$$\boxed{\eta_{th} = 0.3877}$$

To get power: F

$$\dot{W}_{net} = \dot{m}\, w_{net}$$

We need $\dot{m}$, which we can get from previous set up with reheater & regenerater working:

$$\dot{m} = \frac{800 \text{ kW}}{226.801 \text{ kJ/kg}}$$

$$\dot{m} = 3.527 \text{ kg/s}$$

Now, the new configuration produces:

$$\dot{W}_{net} = 3.527 \tfrac{\text{kg}}{\text{s}} \times 116.327 \tfrac{\text{kJ}}{\text{kg}}$$

$$\boxed{\dot{W}_{net} = 410.322 \text{ kW}}$$

SUMMARY

The effectiveness of the regenerator is 18.276%. After turning off the reheater, the working fluid must be rerouted to avoid the regenerator because the exhaust gases are colder than the air coming out of the compressors. With them out of the cycle the efficiency became 0.3877 and the power produced became 410.322 kW.

G

MATERIAL

Air

ANALYSIS

It is important to realize that the regenerator must be stopped as we would be wasting energy.

The efficiency improved because the regenerator was removed and it had a bad effectiveness.

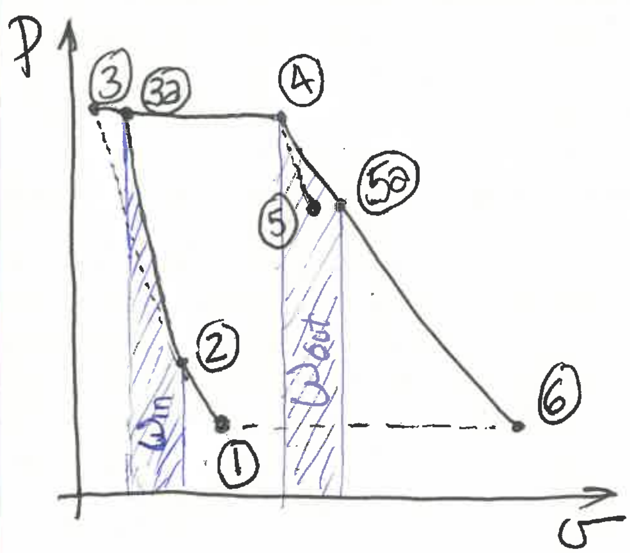
Note from figure on the test that the regenerator should have been designed for an effectiveness of at least 0.6!

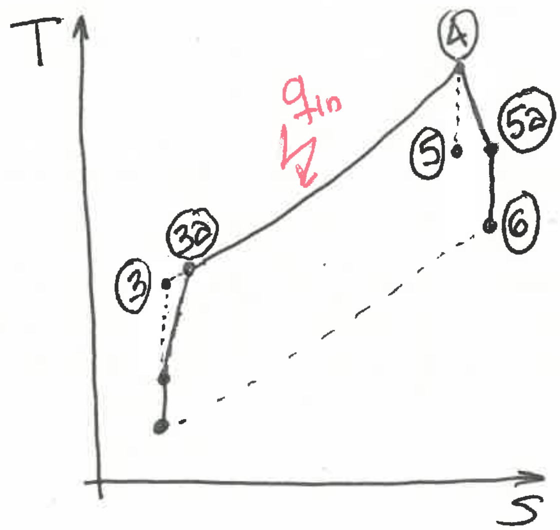
The power produced was reduced to almost half after we removed half of the provided heat.

(2) PURPOSE | H |

Calculate the propulsive efficiency of a jet propulsion cycle with air with C_p & C_v variable and the isentropic efficiencies of the compressor and the turbine of 80% and 85% respectively.

DRAWINGS & DIAGRAMS





SOURCES

Congel & Boles. "Thermodynamics - An Engineering Approach" 8th edition. McGraw Hill. 2015

DESIGN CONSIDERATIONS

1) Air as ideal gas ($R = 0.287 \frac{kJ}{kg \cdot K}$)
2) C_p & C_v variable
3) $\eta_c = 0.8$; $\eta_T = 0.85$
4) Constant pressure heat addition

DATA & VARIABLES

$V_{aircraf} = 240$ m/s $P_1 = 45$ kPa $T_1 = -13°C$ $D_{inlet} = 1.6$ m $r_p = 13$ $T_{inlet\ turb} = 557°C$

PROCEDURE & CALCULATIONS

Let us get all the states and the fluid velocities where corresponds

(1) —Isent, Diffuser→ (2) —Isent→ (3) (3a) —P const→ (4) —Isent, $W_c = W_T$→ (5) (5a) —Isent, Nozzle→ (6)

State 1

$P_1 = 45\,kPa$

$T_1 = 260.15\,K$

$V_1 = 240\,\frac{m}{s}$

Table A-17

$h_1 = 260.24\,\frac{kJ}{kg}$

$P_{r_1} = 0.8423$

State 2

$V_2 = 0\,m/s$

Using 1st law

$\frac{V_1^2}{2} + h_1 = \frac{V_2^2}{2} + h_2$ (with $V_2 = 0$)

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

$= 260.24\,\frac{kJ}{kg} + \frac{(240\,m/s)^2}{2}\left(\frac{1\,kJ/kg}{1000\,m^2/s^2}\right)$

$h_2 = 289.04\,\frac{kJ}{kg}$

Table A-17

$T_2 = 288.884\,K$

$P_{r_2} = 1.2149$

State 3

$P_3 = 13 P_2$

$P_3 = 843.778\,kPa$

$P_{r_3} = P_{r_2}\left(\frac{P_3}{P_2}\right)$

$P_{r_3} = 15.7937$

Table A-17

$T_3 = 574.986\,K$

$h_3 = 601.776\,\frac{kJ}{kg}$

For actual state

$h_{3a} = \frac{h_3 - h_2}{\eta_c} + h_2$

$h_{3a} = 699.930\,\frac{kJ}{kg}$

Table A-17

$T_{3a} = 668.84\,K$

State 4

$P_4 = P_3$

$T_4 = 830.15\,K$

$P_4 = 843.778\,kPa$

Table A-17

$P_{r_4} = 55.133$

State 5

$V_5 = 0\,\frac{m}{s}$

$W_{C_a} = W_{T_a}$

$h_4 - h_{5a} = h_{3a} - h_2$

$h_{5a} = h_4 - h_{3a} + h_2$

$h_{5a} = 464.301\,\frac{kJ}{kg}$

Table A-17

$T_{5a} = 462.232\,K$

To get the ideal state (which will give us P)

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

$h_5 = 395.319\,\frac{kJ}{kg}$

Table A-17

$P_{r_5} = 3.624$

$P_5 = P_4\left(\frac{P_{r_5}}{P_{r_4}}\right)$

$P_5 = 55.463\,kPa$

State 6

$P_6 = 45\,kPa$

$P_{r_6} = P_{r_5}\left(\frac{P_6}{P_5}\right)$

$P_{r_6} = 2.940$

Table A-17

$T_6 = 371.69\,K$

$h_6 = 372.377\,\frac{kJ}{kg}$

Using 1st law

$\frac{V_5^2}{2} + h_{5a} = \frac{V_6^2}{2} + h_6$ (with $V_5 = 0$)

$\frac{V_6^2}{2} = (h_{5a} - h_6)\left(\frac{1000\,m^2/s^2}{1\,kJ/kg}\right)$

$V_6 = 428.77\,m/s$

H

J

For the propulsion force:

$$F = \frac{V_1}{\upsilon_1}\frac{\pi}{4}D^2(V_6 - V_1)$$

$$F = 54906.99\ N$$

For the propulsion power

$$\dot{W}_p = F \times V_1$$

$$\dot{W}_p = 13.178\ MW$$

Thus, the propulsive efficiency:

$$\eta_p = \frac{\dot{W}_p}{\dot{Q}_{in}} = \frac{\dot{W}_p}{\frac{1}{\upsilon_1} \times V_1 \times \frac{\pi}{4}D^2 \times (h_4 - h_{3a})}$$

$$\boxed{\eta_p = 0.258}$$

Using the numbers from the solved problem we can find that the propulsive efficiency is

$$\eta_p = 0.338$$

SUMMARY

K

The propulsive efficiency treating the air with C_p & C_v constant and ideal compressor and turbine is 0.338. Treating the compressor and turbine with their efficiencies and taking the air with C_p & C_v variable, the propulsive efficiency drops to 0.258.

The pressure and temperatures of each actual states are:

	T (K)	P (KPa)
1	260.15	45.00
2	288.884	64.91
3	668.87	843.778
4	830.15	843.778
5	462.232	55.463
6	371.69	45.00

MATERIAL

Air

ANALYSIS

The propulsive efficiency drops because the compressor and the turbine were treated as "real" with efficiencies. The conditions at the exit of the turbine (P&T) dropped also because of the isentropic efficiencies.