Period of Examinations
Summer semester 2021 / September

Your course of study: __________ **(Use the abbreviation ME or IE or SE respectively)**

Module Title: **ME 3 2708 / SE 3 2708 / IE 5 2708 Thermodynamics**

Family Name: ____________________

First Name: ____________________

Student No.: ____________________

I hereby confirm in lieu of an oath that I am the person who was admitted to this examination. Further, I confirm that the submitted work is my own and was prepared without the use of any unauthorised aides or materials*. I am fully aware of the legal consequences of making a false declaration.

Date: 20.09.2021 **Signature:** ______________________________

*Authorised aides and materials are:

- Non-programmable pocket calculator
- Geometrical tools (no coloured pencils!)
- All lectures slides and exercises available in the Moodle course "Thermodynamics B.Sc. WS20/21"
- Your personal handwritten notes
- Moran/Shapiro Steam Tables A2 – A6 (either printed or on the screen)
- Textbooks -neither as hardcopy nor as e-book- are not permitted!

Examination form: Written exam

Points: 75

Duration: 120 Minutes

All calculations and sketches can be made on your own paper sheets.

Each sheet must contain your name, your student number and your signature.

Tablets or comparable devices are not permitted.

Please write legibly. Thank you very much and good luck.

Register No.:____________________

FOR INTERNAL USE ONLY:

	Q1	Q2	Q3	Q4	Q5	Written exam	Stirling motor	Practical Training	Total
Max. Points	15	17	16	7	20	75	13	12	100
Achieved									
						≥ 38 Yes | No		Grade	

Graded by		Checked by

Final Grade

Regular grading key.	
Adjusted grading key. (Please add the adjusted grading key to the exam-results)	X

Question 1 … Work and polytropic change of state **Points: 15 (7+5+3)**

Q1.1

Nitrogen gas is compressed in a flexible container following a relationship of

$p \cdot v^{1.2} = \text{constant}$.

The mass of the nitrogen is 1.5 kg, and initially the pressure and temperature of the nitrogen are 120 kPa and 15°C, respectively. The compression continues until the volume reaches 0.10 m³.

Determine the final pressure and temperature of the nitrogen, and determine the work done on the nitrogen in the process.

Nitrogen behaves as an ideal gas, i.e. $p \cdot v = R \cdot T$

Given: Specific gas constant of Nitrogen $R = 0.2968 \frac{kJ}{kgK}$

Solution:

$V_1 = 1.068\ m^3$ $p_2 = 2{,}060\ kPa$ $W_{12} = 389\ kJ$

Q1.2

Air at 450 kPa and 20°C fills a piston-cylinder assembly to a volume of 0.075 m³. The air expands, in a constant-temperature process, until the pressure is 150 kPa. The constant-temperature process can be modelled as a polytropic process with n = 1.

Determine the work done by the air as it expands.

Solution:

$W_{12} = 37.1\ kJ$

Q1.3

2.0 kg of water vapor at 500 kPa fills a balloon. The specific volume of the water vapor is 0.37 m³/kg. The water condenses at constant pressure until a liquid-vapor mixture with a specific volume of 0.09 m³/kg is present. Determine the work done in the process.

Solution:

$W_{12} = 280\ kJ$

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Question 2 …. Thermodynamic properties **Points: 17 (8+9)**

Q2.1

Air is located in a piston-cylinder device. The diameter of the cylinder is 12 cm, the mass of the piston is 5 kg, and the acceleration due to gravity is 9.81 m/s². The local atmospheric pressure is 100.5 kPa.

Determine the mass of a set of weights that needs to be added to the top of the piston so that the absolute pressure of the air in the cylinder is 250 kPa.

Solution:

$m = 168\ \text{kg}$

Q2.2

Using Moran/Shapiro Steam Tables steam tables, complete the following chart of thermodynamic properties for water.

$T\,[°C]$	$p\,[bar]$	$v\,[m^3/kg]$	$h\,[kJ/kg]$	Phase / Quality
150	4.758	0.0990179	1160.775	$x = 0.25$
151.9	5	0.2687574	2,150	$x = 0.716$
400	10	0.3066	3263.9	Superheated (x is undefied)

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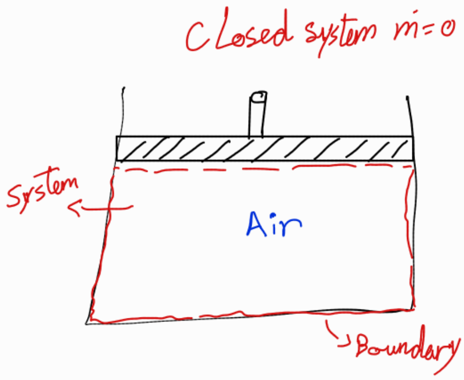
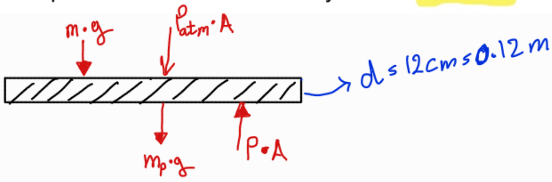
Determine the mass of a set of weights that needs to be added to the top of the piston so that the absolute pressure of the air in the cylinder is 250 kPa.





$$\sum F = 0 = P \cdot A - P_{atm} \cdot A - m_p \cdot g - mg \Longrightarrow m = \frac{1}{g}\left(P \cdot A - P_{atm} \cdot A\right) - m_p$$

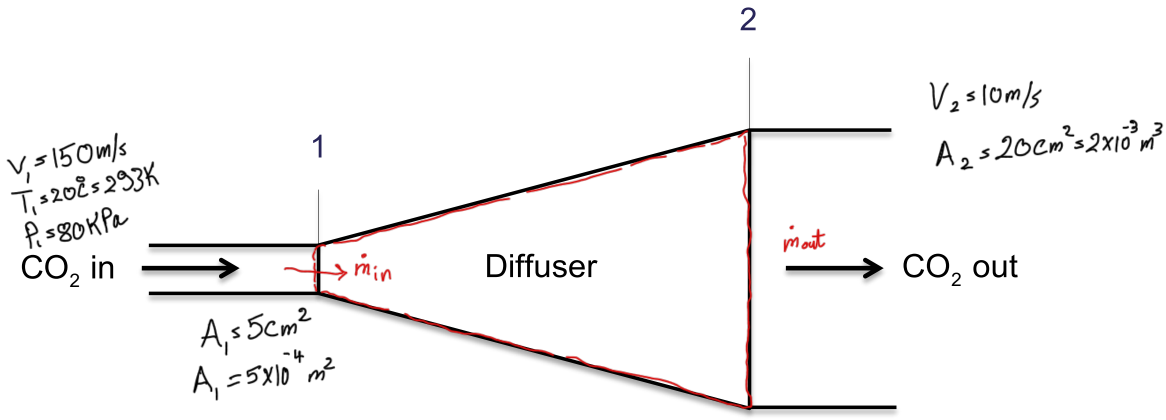
$$A = \frac{\pi}{4} d^2 \Longrightarrow \boxed{m = \frac{\pi}{4g} d^2 \left(P - P_{atm}\right) - m_p}$$ solution

$$m = \frac{\pi\,(0.12\,\cancel{m})^2}{4\,(9.81\,\cancel{m/s^2})} \cdot 10^3 \frac{\cancel{Pa}}{\cancel{kPa}} \left(250\,\cancel{kPa} - 100.5\,\cancel{kPa}\right) - 5\,Kg \Longrightarrow m = 167.36\,Kg$$

Pa: N/m^2, $Kg \cdot m/s^2$

Question 3 …. 1st rule of thermodynamics **Points: 16 (8+8)**

An insulated diffuser receives CO_2 gas with a velocity of 150 m/s, at 20°C and 80 kPa. The diffuser inlet has a cross-sectional area of 5 cm². The CO_2 exits at a velocity of 10 m/s through a cross-sectional area of 20 cm².



Assuming constant specific heat capacity for the CO_2, determine

a) the exit temperature of the CO_2, i.e. T_2 [°C]

b) the exit pressure of the CO_2, i.e. p_2 [kPa]

Assumptions:

→ Horizontal arrangement

→ Steady state flow

→ CO_2 behaves as an ideal gas

→ Constant specific heat capacity $\bar{c}_{CO2} = 0.842\,\frac{kJ}{kg \cdot K}$

→ Specific gas constant $R_{CO2} = 0.1889\,\frac{kJ}{kg \cdot K}$

Solution:

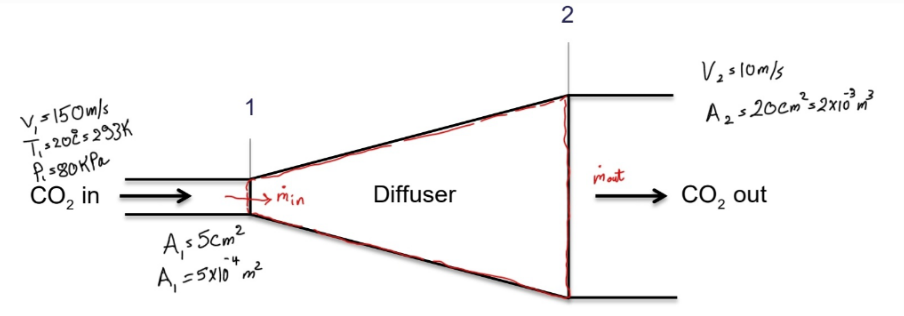
a) $T_2 = 33.3°C$

b) $p_2 = 314\,kPa$

Q3

open system

$\dot m_{in} = \dot m_{out} = \dot m$



a) 1st Law of thermodynamics: $\underbrace{\cancel{\frac{dE}{dt}}}_{\text{Steady-state}}^{0} = \cancel{\sum \dot Q}^{0} + \cancel{\sum \dot W}^{0} + \sum \dot m \cdot e$

$e = \underbrace{u + P\cdot v}_{h} + e_{Ke} + \cancel{e_p}^{0}$ neglected

$\therefore \dot m\left(h_{in} + \frac{1}{2}V_1^2 - h_{out} - \frac{1}{2}V_2^2\right) = 0 \Rightarrow h_{out} - h_{in} = \frac{1}{2}(V_1^2 - V_2^2)$

$\bar C_{CO_2}$ = cons.

$dh = \int_1^2 C_p\, dT = \bar C_{CO_2}(T_2 - T_1) \Longrightarrow \bar C_{CO_2}(T_2 - T_1) = \frac{1}{2}(V_1^2 - V_2^2)$

$\therefore T_2 = \frac{V_1^2 - V_2^2}{2\bar C_{CO_2}} + T_1 = \frac{(150m/s)^2 - (10m/s)^2}{2(0.842\, \cancel{K}J/Kg\cdot K)\times 10^3 \frac{J}{\cancel{KJ}}} + 293K$

$T_2 = 306.3K = 33.3\,°C$

b) Ideal gas law $P_1 v_1 = RT_1$

only equations

$P_2 v_2 = RT_2 \Rightarrow \boxed{P_2 = \frac{RT_2}{\underset{?}{v_2}}}$ solution

$\dot m = \rho_2 \cdot V_2 \cdot A_2 = \frac{1}{v_2}\cdot V_2 \cdot A_2$

$v_2 = \frac{V_2 \cdot A_2}{\dot m}$

$\dot m = \frac{1}{v_1} V_1 \cdot A_1$, $v_1 = \frac{RT_1}{P_1}$

$\Rightarrow \dot m = \frac{P_1 \cdot V_1 \cdot A_1}{RT_1} \Rightarrow v_2 = \frac{V_2 \cdot A_2 \cdot R \cdot T_1}{P_1 \cdot V_1 \cdot A_1}$

$P_2 = \frac{\cancel{R}\cdot T_2}{\frac{V_2 \cdot A_2 \cdot \cancel{R} \cdot T_1}{P_1 \cdot V_1 \cdot A_1}} = \frac{P_1 \cdot V_1 \cdot A_1 \cdot T_2}{V_2 \cdot A_2 \cdot T_1} = \frac{80KPa\,(150m/s)(5\times10^{-4}m^2)(306.3K)}{(10m/s)(2\times10^{-3}m^2)(293K)}$

$v_1 = \frac{RT_1}{P_1} = \frac{0.1889\, \cancel{KJ}^{KN\cdot m}/Kg\cdot \cancel{K}\,(293\cancel{K})}{80\,\cancel{KPa}\ KN/m^2} = 0.692\, m^3/Kg$

$\dot m = \rho_1 \cdot V_1 \cdot A_1 = \frac{V_1 \cdot A_1}{v_1} = \frac{150 m/s\,(5\times10^{-4}m^2)}{0.692\, m^3/Kg} = 0.1084\, Kg/s$

$\dot m = \rho_2 \cdot V_2 \cdot A_2 \Rightarrow \dot m = \frac{1}{v_2}\cdot V_2 \cdot A_2 \Longrightarrow v_2 = \frac{V_2 \cdot A_2}{\dot m} = 0.1845\, m^3/Kg$

$P_2 v_2 = RT_2 \Rightarrow \boxed{P_2 = \frac{RT_2}{v_2}} = 313.62\, KPa$

Solution

Register No.:____________________

Question 4 …. 2^{nd} rule of thermodynamics **Points: 7**

A heat transformer extracts heat from a large groundwater reservoir at a temperature of T_C = 10°C. The extracted heat flow amounts to 100 kW. Operating at steady-state conditions, a heat flow of 15 kW is provided for heating purposes at a temperature of T_H = 60°C, while a heat flow of 85 kW is released to the environment. The temperature of the environment can be assumed as T_E = - 6°C.

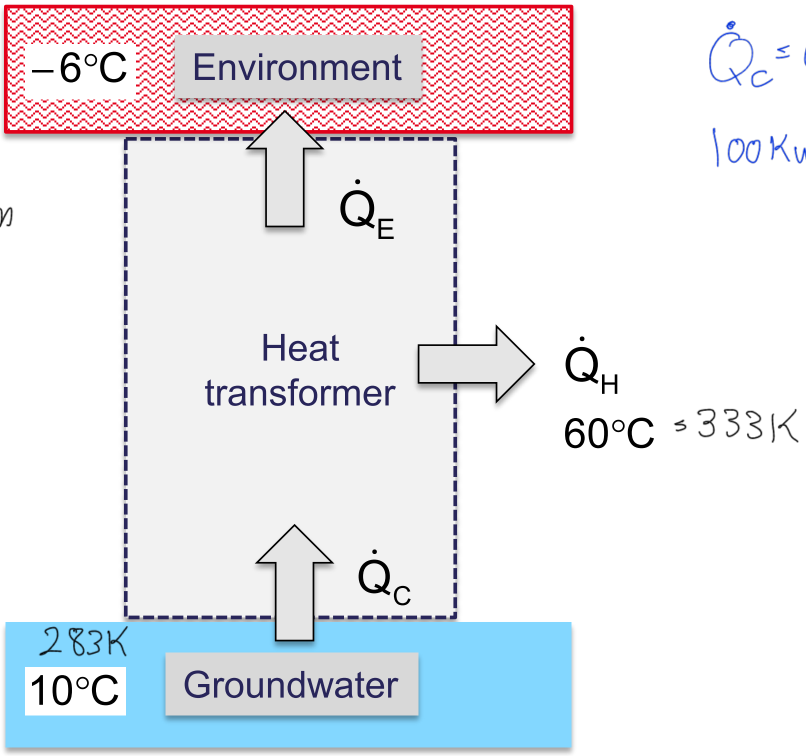
Is it possible to operate a real transformer under these conditions?

Provide proof by applying the 1^{st} and 2^{nd} rule of thermodynamics.

1st Law of thermodynamics: $\frac{\cancel{dE}}{dt} = \sum \dot{Q} + \cancel{\sum P} + \sum \cancel{\dot{m}e}$

$0 \quad 0$

Closed system



$\dot{Q}_C = \dot{Q}_E + \dot{Q}_H$

100 KW = 85KW + 15KW

2nd Law: $\frac{\dot{Q}_{in}}{T_H} - \frac{\dot{Q}_{out}}{T_C} \leq -\sigma$

$\Rightarrow \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H} - \frac{\dot{Q}_E}{T_E} = -\sigma \Rightarrow \frac{100KW}{283} - \frac{15KW}{333K} - \frac{85KW}{267K} = -\sigma$

$\therefore \sigma \leq 10.04$ W/K > 0

Possible.

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Question 5 …. Rankine cycle **Points: 20 (3+6+6+5)**

Steam is the working fluid in an ideal Rankine cycle with superheating and reheating.

Steam enters the first-stage (high pressure) turbine at p_1 = 60 bar, T_1 = 600°C, and expands to p_2 = 10 bar. It is then reheated to 600°C before entering the second-stage (low pressure) turbine, where it expands to the condenser pressure of 0.35 bar.

a) Draw a process flow sheet of the cycle comprising all components, which are required to operate the cycle properly. Label all states starting with State 1 at the inlet of the high-pressure turbine.

b) Sketch the cycle on T-s coordinates and specify the nature of each process (adiabatic or isothermal or polytropic or isentropic or isobaric, expansion or compression and so on ….).

c) Determine the properties of each state by using Moran/Shapiro tables and fill in the table below. (T_2, T_4, and T_6 do not need to be determined.)

d) Determine the thermal efficiency of the cycle.

Assumptions:

→ Label the states as follows
1 … Inlet of high-pressure turbine
2 … Exit of high-pressure turbine
… and so on …

→ Neglect kinetic and potential energy effects.

→ Turbine and pump are operating adiabatically.

→ Power demand of the pump is negligible.

→ Interpolation not required. An educated guess is sufficient.

Solution:

$\eta_{thermal}$ = 0.4

$$\eta_{th} = \frac{(h_1-h_2)+(h_3-h_4)\cancel{-(h_6-h_5)}^{\,0}}{(h_1-h_6)+(h_3-h_2)} \approx 0.381$$

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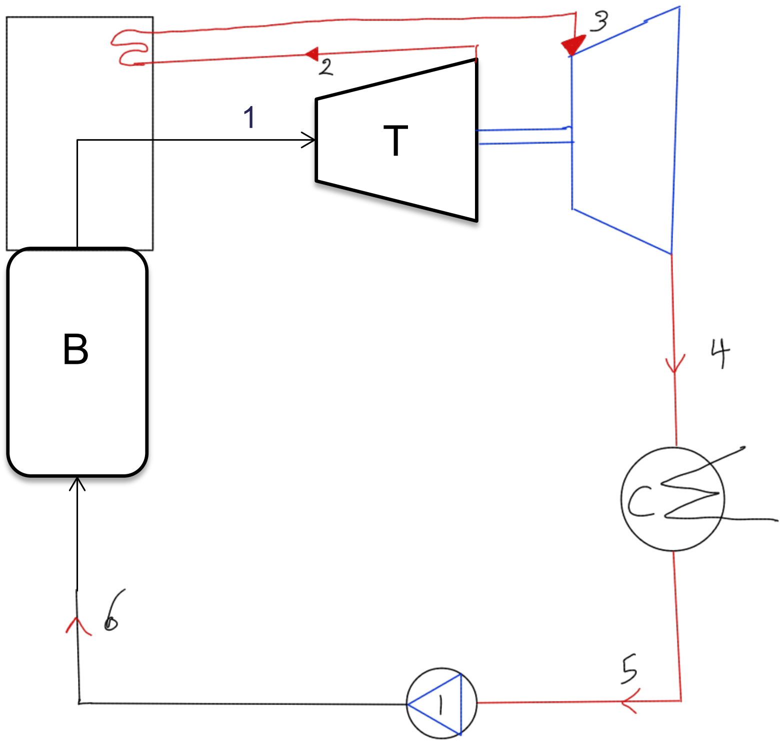
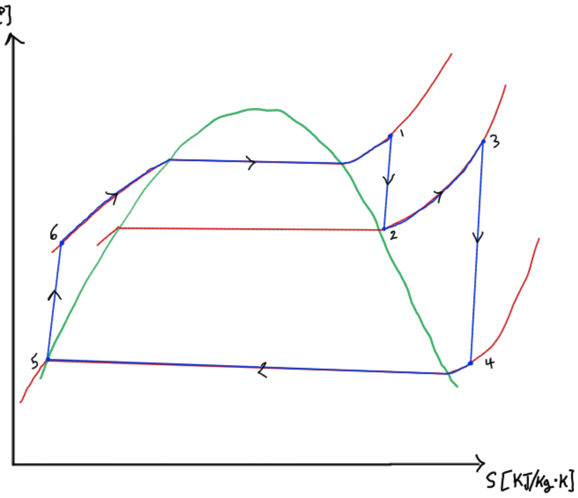
Template for process flow sheet





	p [bar]	T [°C]	x [–]	h [kJ/kg]	s [kJ/kgK]
1	60	600	Superheated	3658.4	7.1677
2	10	$T_2 \approx 312$	superheated	$h_2 = 3076.7$	$S_2 = S_1 = 7.1677$
3	$P_3 = P_2 = 10$	600	Superheated	3697.9	8.029
4	0.35	$T_4 \approx 140$	Superheated	2764.4	$S_4 = S_3 = 8.029$
5	0.35	72.69	0	303	7.7193
6	60	-----	—	303	7.7193

End of exam