Delft University of Technology **DEPARTMENT OF AEROSPACE ENGINEERING**	
Course: Physics I (AE1-104)	Course year: 1
Date: 03-02-2012	Time: 14:00-17:00
Student name and initials (capital letters):……………………………………	
Student number: ……………………………………	
Language of the lectures you followed (cross as appropriate) ☐ Dutch ☐ English	

Instructions

Write your answers using the blank space on the page where the problem is given.
Or use the back of the page, if necessary.
Deliver ONLY the present booklet at the end of the exam. (do not include scrap paper or any other sheet)
PLEASE TAKE NOTE OF THE PARAMETER VALUES LISTED AT THE BOTTOM OF THIS PAGE
YOU CAN USE THE OFFICIAL EQUATIONS SHEET. THE USE OF OTHER INFORMATION CARRIERS IS STRICTLY FORBIDDEN.

Problem 1: (15 points)

True or false exercise (12pts 1 error; 10 pts 2 errors; 8pts 3 errors; 6pts 4 errors; 4pts 5 errors, 2pts 6 errors; 0pts >6 errors)

Statement	**True**	**False**
1 – Hydrogen has a higher gas constant than Oxygen	X	
2 – Autoignition increases the efficiency of reciprocating engines		X
3 – Temperature is an extensive system property		X
4 – No device can transfer heat from a cold to a hot object without work input	X	
5 – Heat transfer by conduction is less than by convection	X	
6 – A system with constant volume cannot produce boundary work	X	
7 – Electrical heating is regarded as energy exchange by work	X	
8 – System entropy is reduced when cooling it	X	
9 – An ideal thermodynamic process must occur at constant temperature		X
10 – The Carnot cycle is internally reversible	X	
11 – The efficiency of a hydroelectric installation can be higher than that of a diesel engine	X	
12 – In a gas turbine engine the air enthalpy increases in the turbine		X

APPENDIX

Universal gas constant: R = 8.314 J/mol · K
Gas constant for air: R_{air} = 287 J/kg · K
Specific heat at constant pressure for air: c_p = 1008 J/kg · K
Ratio of specific heats for air: k = 1.4

Problem 2 (15 points)

A wind turbine is rotating at 15 rpm under steady wind. The air flows through the turbine at a rate of 42,000 kg/s. The tip velocity of the turbine is measured to be 250 km/h. If 180 kW is produced by the turbine, determine

a) The average velocity of the air
b) The conversion efficiency of the turbine

Take the density of the air to be 1.31 kg/m^3

Solution (2 ANSWERS REQUIRED !!)

2-74 A wind turbine produces 180 kW of power. The average velocity of the air and the conversion efficiency of the turbine are to be determined.

Assumptions The wind turbine operates steadily.

Properties The density of air is given to be 1.31 kg/m^3.

Analysis (*a*) The blade diameter and the blade span area are

$$D = \frac{V_{tip}}{\pi \dot{n}} = \frac{(250\text{ km/h})\left(\frac{1\text{ m/s}}{3.6\text{ km/h}}\right)}{\pi(15\text{ L/min})\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 88.42\text{ m}$$

$$A = \frac{\pi D^2}{4} = \frac{\pi(88.42\text{ m})^2}{4} = 6140\text{ m}^2$$

Then the average velocity of air through the wind turbine becomes

$$V = \frac{\dot{m}}{\rho A} = \frac{42{,}000\text{ kg/s}}{(1.31\text{ kg/m}^3)(6140\text{ m}^2)} = \mathbf{5.23\ m/s}$$

(*b*) The kinetic energy of the air flowing through the turbine is

$$\dot{\text{KE}} = \frac{1}{2}\dot{m}V^2 = \frac{1}{2}(42{,}000\text{ kg/s})(5.23\text{ m/s})^2 = 574.3\text{ kW}$$

Then the conversion efficiency of the turbine becomes

$$\eta = \frac{\dot{W}}{\dot{\text{KE}}} = \frac{180\text{ kW}}{574.3\text{ kW}} = \mathbf{0.313} = \mathbf{31.3\%}$$

Discussion Note that about one-third of the kinetic energy of the wind is converted to power by the wind turbine, which is typical of actual turbines.

Problem 3 (15 points)

A friction-less piston cylinder device initially contains air at 200 kPa and 0.2 m^3. At this stage a linear spring (i.e. the spring load is proportional to the displacement) is touching the piston without exerting a force on it. The air is now heated to a final volume of 0.5 m^3 and a pressure of 800 kPa.

a) Plot the process in a P-V diagram.
b) Determine the total amount of work done by the air in the cylinder.
c) Determine the work done against the spring.

Solution (3 ANSWERS REQUIRED)

4-127 A cylinder equipped with an external spring is initially filled with air at a specified state. Heat is transferred to the air, and both the temperature and pressure rise. The total boundary work done by the air, and the amount of work done against the spring are to be determined, and the process is to be shown on a *P-v* diagram.

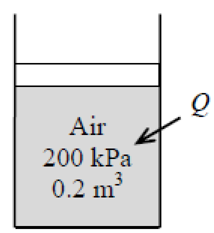
Assumptions **1** The process is quasi-equilibrium. **2** The spring is a linear spring.

Analysis (*a*) The pressure of the gas changes linearly with volume during this process, and thus the process curve on a *P-V* diagram will be a straight line. Then the boundary work during this process is simply the area under the process curve, which is a trapezoidal. Thus,

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1)$$

$$= \frac{(200 + 800)\text{kPa}}{2}(0.5 - 0.2)\text{m}^3\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{150\ kJ}$$

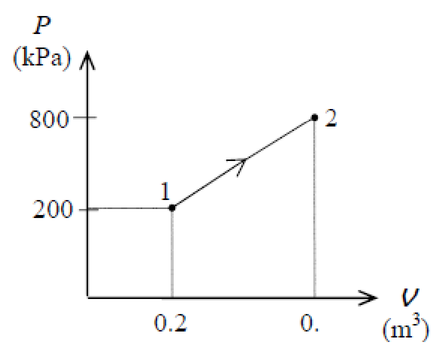


(*b*) If there were no spring, we would have a constant pressure process at P = 200 kPa. The work done during this process is

$$W_{b,\text{out,no spring}} = \int_1^2 P\,dV = P(V_2 - V_1)$$

$$= (200\ \text{kPa})(0.5 - 0.2)\text{m}^3/\text{kg}\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 60\ \text{kJ}$$



Thus,

$$W_{\text{spring}} = W_b - W_{b,\text{no spring}} = 150 - 60 = \mathbf{90\ kJ}$$

Problem 4 (20 points)

Steam enters an adiabatic turbine at a pressure of 7 MPa, a temperature of 600 ^{0}C and a velocity of 80 m/s. It leaves the turbine at 50 kPa, 150 ^{0}C and 140 m/s.

If the power output of the turbine is 6 MW, determine:

a) The mass flow rate of the steam going through the turbine

b) The isentropic efficiency of the turbine

TABLE A–6

Superheated water

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.01 MPa (45.81°C)*				P = 0.05 MPa (81.32°C)				P = 0.10 MPa (99.61°C)			
Sat.†	14.670	2437.2	2583.9	8.1488	3.2403	2483.2	2645.2	7.5931	1.6941	2505.6	2675.0	7.3589
50	14.867	2443.3	2592.0	8.1741								
100	17.196	2515.5	2687.5	8.4489	3.4187	2511.5	2682.4	7.6953	1.6959	2506.2	2675.8	7.3611
150	19.513	2587.9	2783.0	8.6893	3.8897	2585.7	2780.2	7.9413	1.9367	2582.9	2776.6	7.6148
200	21.826	2661.4	2879.6	8.9049	4.3562	2660.0	2877.8	8.1592	2.1724	2658.2	2875.5	7.8356
250	24.136	2736.1	2977.5	9.1015	4.8206	2735.1	2976.2	8.3568	2.4062	2733.9	2974.5	8.0346
300	26.446	2812.3	3076.7	9.2827	5.2841	2811.6	3075.8	8.5387	2.6389	2810.7	3074.5	8.2172
400	31.063	2969.3	3280.0	9.6094	6.2094	2968.9	3279.3	8.8659	3.1027	2968.3	3278.6	8.5452
500	35.680	3132.9	3489.7	9.8998	7.1338	3132.6	3489.3	9.1566	3.5655	3132.2	3488.7	8.8362
600	40.296	3303.3	3706.3	10.1631	8.0577	3303.1	3706.0	9.4201	4.0279	3302.8	3705.6	9.0999
700	44.911	3480.8	3929.9	10.4056	8.9813	3480.6	3929.7	9.6626	4.4900	3480.4	3929.4	9.3424
800	49.527	3665.4	4160.6	10.6312	9.9047	3665.2	4160.4	9.8883	4.9519	3665.0	4160.2	9.5682
900	54.143	3856.9	4398.3	10.8429	10.8280	3856.8	4398.2	10.1000	5.4137	3856.7	4398.0	9.7800
1000	58.758	4055.3	4642.8	11.0429	11.7513	4055.2	4642.7	10.3000	5.8755	4055.0	4642.6	9.9800
1100	63.373	4260.0	4893.8	11.2326	12.6745	4259.9	4893.7	10.4897	6.3372	4259.8	4893.6	10.1698
1200	67.989	4470.9	5150.8	11.4132	13.5977	4470.8	5150.7	10.6704	6.7988	4470.7	5150.6	10.3504
1300	72.604	4687.4	5413.4	11.5857	14.5209	4687.3	5413.3	10.8429	7.2605	4687.2	5413.3	10.5229

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 6.0 MPa (275.59°C)				P = 7.0 MPa (285.83°C)				P = 8.0 MPa (295.01°C)			
Sat.	0.03245	2589.9	2784.6	5.8902	0.027378	2581.0	2772.6	5.8148	0.023525	2570.5	2758.7	5.7450
300	0.03619	2668.4	2885.6	6.0703	0.029492	2633.5	2839.9	5.9337	0.024279	2592.3	2786.5	5.7937
350	0.04225	2790.4	3043.9	6.3357	0.035262	2770.1	3016.9	6.2305	0.029975	2748.3	2988.1	6.1321
400	0.04742	2893.7	3178.3	6.5432	0.039958	2879.5	3159.2	6.4502	0.034344	2864.6	3139.4	6.3658
450	0.05217	2989.9	3302.9	6.7219	0.044187	2979.0	3288.3	6.6353	0.038194	2967.8	3273.3	6.5579
500	0.05667	3083.1	3423.1	6.8826	0.048157	3074.3	3411.4	6.8000	0.041767	3065.4	3399.5	6.7266
550	0.06102	3175.2	3541.3	7.0308	0.051966	3167.9	3531.6	6.9507	0.045172	3160.5	3521.8	6.8800
600	0.06527	3267.2	3658.8	7.1693	0.055665	3261.0	3650.6	7.0910	0.048463	3254.7	3642.4	7.0221
700	0.07355	3453.0	3894.3	7.4247	0.062850	3448.3	3888.3	7.3487	0.054829	3443.6	3882.2	7.2822
800	0.08165	3643.2	4133.1	7.6582	0.069856	3639.5	4128.5	7.5836	0.061011	3635.7	4123.8	7.5185
900	0.08964	3838.8	4376.6	7.8751	0.076750	3835.7	4373.0	7.8014	0.067082	3832.7	4369.3	7.7372
1000	0.09756	4040.1	4625.4	8.0786	0.083571	4037.5	4622.5	8.0055	0.073079	4035.0	4619.6	7.9419
1100	0.10543	4247.1	4879.7	8.2709	0.090341	4245.0	4877.4	8.1982	0.079025	4242.8	4875.0	8.1350
1200	0.11326	4459.8	5139.4	8.4534	0.097075	4457.9	5137.4	8.3810	0.084934	4456.1	5135.5	8.3181
1300	0.12107	4677.7	5404.1	8.6273	0.103781	4676.1	5402.6	8.5551	0.090817	4674.5	5401.0	8.4925

Solution (2 ANSWERS REQUIRED)

7-132 Steam enters an adiabatic turbine at a specified state, and leaves at a specified state. The mass flow rate of the steam and the isentropic efficiency are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Potential energy changes are negligible. **3** The device is adiabatic and thus heat transfer is negligible.

Analysis (*a*) From the steam tables (Tables A-4 and A-6),

$$\left.\begin{array}{l} P_1 = 7 \text{ MPa} \\ T_1 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3650.6 \text{ kJ/kg} \\ s_1 = 7.0910 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 50 \text{ kPa} \\ T_2 = 150°\text{C} \end{array}\right\} h_{2a} = 2780.2 \text{ kJ/kg}$$

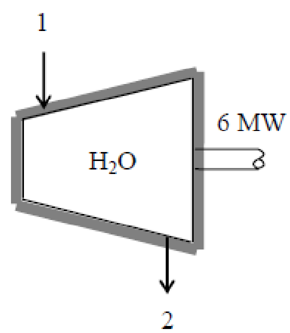
There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}(h_1 + V_1^2/2) = \dot{W}_{\text{a,out}} + \dot{m}(h_2 + V_1^2/2) \quad (\text{since } \dot{Q} \cong \Delta\text{pe} \cong 0)$$

$$\dot{W}_{\text{a,out}} = -\dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}\right)$$



Substituting, the mass flow rate of the steam is determined to be

$$6000 \text{ kJ/s} = -\dot{m}\left(2780.2 - 3650.6 + \frac{(140 \text{ m/s})^2 - (80 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right)$$

$$\dot{m} = \mathbf{6.95 \ kg/s}$$

(*b*) The isentropic exit enthalpy of the steam and the power output of the isentropic turbine are

$$\left.\begin{array}{l} P_{2s} = 50 \text{ kPa} \\ s_{2s} = s_1 \end{array}\right\} \begin{array}{l} x_{2s} = \dfrac{s_{2s} - s_f}{s_{fg}} = \dfrac{7.0910 - 1.0912}{6.5019} = 0.9228 \\ h_{2s} = h_f + x_{2s} h_{fg} = 340.54 + (0.9228)(2304.7) = 2467.3 \text{ kJ/kg} \end{array}$$

and

$$\dot{W}_{\text{s,out}} = -\dot{m}\left(h_{2s} - h_1 + \left\{\left(V_2^2 - V_1^2\right)/2\right\}\right)$$

$$\dot{W}_{\text{s,out}} = -(6.95 \text{ kg/s})\left(2467.3 - 3650.6 + \frac{(140 \text{ m/s})^2 - (80 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right)$$

$$= 8174 \text{ kW}$$

Then the isentropic efficiency of the turbine becomes

$$\eta_T = \frac{\dot{W}_a}{\dot{W}_s} = \frac{6000 \text{ kW}}{8174 \text{ kW}} = 0.734 = \mathbf{73.4\%}$$

Problem 5 (15 points)

An Ideal Diesel cycle has a maximum cycle temperature of 200 ^{0}C and a cut-off ratio r_c = 1.2. The state of the air at the beginning of the compression is P_1= 95 kPa and T_1 = 15 ^{0}C. The cycle is executed in a four-stroke, 8-cylinder engine with a cylinder bore of 10 cm and a piston stroke of 12 cm. The minimum volume enclosed in the cylinder is 5% of the maximum cylinder volume. Determine:

a) the air temperature at the end of compression and before ignition
b) the power produced by this engine when it operates at 1600 rpm. Use constant specific heats at room temperature.

Solution (2 answers required)

9-111 A Brayton cycle with regeneration produces 150 kW power. The rates of heat addition and rejection are to be determined.

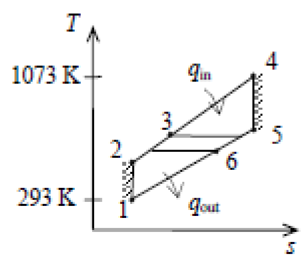
Assumptions **1** The air standard assumptions are applicable. **2** Air is an ideal gas with constant specific heats at room temperature. **3** Kinetic and potential energy changes are negligible.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg.K and k = 1.4 (Table A-2a).

Analysis According to the isentropic process expressions for an ideal gas,

$$T_2 = T_1 r_p^{(k-1)/k} = (293\text{ K})(8)^{0.4/1.4} = 530.8\text{ K}$$

$$T_5 = T_4\left(\frac{1}{r_p}\right)^{(k-1)/k} = (1073\text{ K})\left(\frac{1}{8}\right)^{0.4/1.4} = 592.3\text{ K}$$



When the first law is applied to the heat exchanger, the result is

$$T_3 - T_2 = T_5 - T_6$$

while the regenerator temperature specification gives

$$T_3 = T_5 - 10 = 592.3 - 10 = 582.3\text{ K}$$

The simultaneous solution of these two results gives

$$T_6 = T_5 - (T_3 - T_2) = 592.3 - (582.3 - 530.8) = 540.8\text{ K}$$

Application of the first law to the turbine and compressor gives

$$\begin{aligned} w_{net} &= c_p(T_4 - T_5) - c_p(T_2 - T_1) \\ &= (1.005\text{ kJ/kg}\cdot\text{K})(1073 - 592.3)\text{ K} - (1.005\text{ kJ/kg}\cdot\text{K})(530.8 - 293)\text{ K} \\ &= 244.1\text{ kJ/kg} \end{aligned}$$

Then,

$$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{150\text{ kW}}{244.1\text{ kJ/kg}} = 0.6145\text{ kg/s}$$

Applying the first law to the combustion chamber produces

$$\dot{Q}_{in} = \dot{m}c_p(T_4 - T_3) = (0.6145\text{ kg/s})(1.005\text{ kJ/kg}\cdot\text{K})(1073 - 582.3)\text{K} = \mathbf{303.0\ kW}$$

Similarly,

$$\dot{Q}_{out} = \dot{m}c_p(T_6 - T_1) = (0.6145\text{ kg/s})(1.005\text{ kJ/kg}\cdot\text{K})(540.8 - 293)\text{K} = \mathbf{153.0\ kW}$$

Problem 6 (20 points)

This question deals with a small gas turbine with a regenerator. Air enters the compressor of the engine at 100 kPa and a temperature of 20 ^{0}C. The compressor ratio is 8 and the maximum cycle temperature is 800 ^{0}C. The cold air leaves the regenerator at a temperature 10 ^{0}C lower than the hot air stream at the inlet of the regenerator. Assuming both the compressor and the turbine to be isentropic answer the following questions:

a) Sketch the turbine system.
b) Plot the turbine cycle in the T-S plane.
c) Determine the rates of heat addition and rejection of the cycle in case the turbine produces 150 kW. For air assume constant specific heat c_p = 1005 J/kg.K

9-111 A Brayton cycle with regeneration produces 150 kW power. The rates of heat addition and rejection are to be determined.

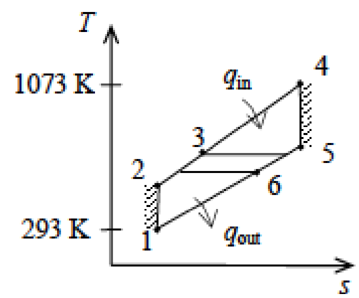
Assumptions **1** The air standard assumptions are applicable. **2** Air is an ideal gas with constant specific heats at room temperature. **3** Kinetic and potential energy changes are negligible.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg.K and k = 1.4 (Table A-2a).

Analysis According to the isentropic process expressions for an ideal gas,

$$T_2 = T_1 r_p^{(k-1)/k} = (293\text{ K})(8)^{0.4/1.4} = 530.8\text{ K}$$

$$T_5 = T_4\left(\frac{1}{r_p}\right)^{(k-1)/k} = (1073\text{ K})\left(\frac{1}{8}\right)^{0.4/1.4} = 592.3\text{ K}$$



When the first law is applied to the heat exchanger, the result is

$$T_3 - T_2 = T_5 - T_6$$

while the regenerator temperature specification gives

$$T_3 = T_5 - 10 = 592.3 - 10 = 582.3\text{ K}$$

The simultaneous solution of these two results gives

$$T_6 = T_5 - (T_3 - T_2) = 592.3 - (582.3 - 530.8) = 540.8\text{ K}$$

Application of the first law to the turbine and compressor gives

$$\begin{aligned} w_{net} &= c_p(T_4 - T_5) - c_p(T_2 - T_1) \\ &= (1.005\text{ kJ/kg}\cdot\text{K})(1073 - 592.3)\text{ K} - (1.005\text{ kJ/kg}\cdot\text{K})(530.8 - 293)\text{ K} \\ &= 244.1\text{ kJ/kg} \end{aligned}$$

Then,

$$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{150\text{ kW}}{244.1\text{ kJ/kg}} = 0.6145\text{ kg/s}$$

Applying the first law to the combustion chamber produces

$$\dot{Q}_{in} = \dot{m}c_p(T_4 - T_3) = (0.6145\text{ kg/s})(1.005\text{ kJ/kg}\cdot\text{K})(1073 - 582.3)\text{K} = \mathbf{303.0\text{ kW}}$$

Similarly,

$$\dot{Q}_{out} = \dot{m}c_p(T_6 - T_1) = (0.6145\text{ kg/s})(1.005\text{ kJ/kg}\cdot\text{K})(540.8 - 293)\text{K} = \mathbf{153.0\text{ kW}}$$