1. (10 marks) A cylinder contains 1 kg of a certain fluid at an initial pressure of 20 bar. A three-step cyclic process is carried out as below

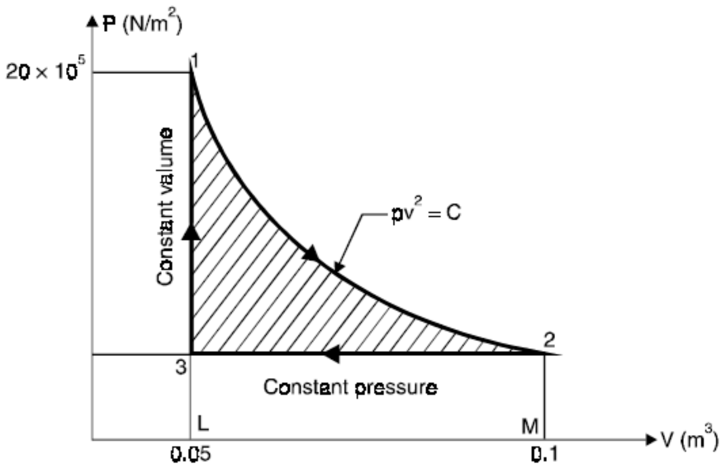
I. **Step1-2**: The fluid is allowed to expand reversibly behind a piston according to $PV^2 = C$ until the volume is doubled.

II. **Step2-3:** The fluid is then cooled reversibly at constant pressure until the piston regains its original position.

III. **Step3-1:** heat is then supplied reversibly with the piston firmly locked in position until the pressure rises to the original value of 20 bar.

Required

a) **(3 marks)** Sketch the given cycle on a PV diagram.



b) **(2 marks)** The net work done by the fluid, for an initial volume of 0.05 m^3 = _______25________ kJ.

c) **(2 marks)** The pressure after **step 1-2** is = _______5________ bar.

d) **(1 mark)** The work in **step 1-2** is = ______50.0_________ kJ.

e) **(1 mark)** The work in **step 2-3** is = ______-25.0________ kJ.

f) **(1 mark)** The work in **step 3-1** is = ________0.0________ kJ.

To solve consider the sequence of steps

I. **Step1-2**: The fluid is allowed to expand reversibly behind a piston according to $PV^2 = C$ until the volume is doubled.

Known is the state at point 1 (P_1 = 20 bar, V_1 = 0.05 m^3). This is a polytropic process in which work is given by

$$W_{12} = \int PdV = \int \frac{C}{V^2} dV = -C\left[\frac{1}{V_2} - \frac{1}{V_1}\right] = -P_1V_1^2\left[\frac{1}{V_2} - \frac{1}{V_1}\right]$$

$$W_{12} = -20\times10^5\times0.05^2\left[\frac{1}{0.10}-\frac{1}{0.05}\right]=50000\,\text{J}.$$

The pressure at state point 2 can be obtained as

$$P_1V_1^{\ 2} = P_2V_2^{\ 2}$$

$$P_2 = P_1\left(\frac{V_1^{\ 2}}{V_2^{\ 2}}\right)=W_{12} = 20\times10^5\left(\frac{0.05}{0.10}\right)=5\times10^5\ \text{Pa}=5\,\text{bar}.$$

II. **Step2-3:** The fluid is then cooled reversibly at constant pressure until the piston regains its original position.

This is an isobaric process for which

$$W_{23} = \int PdV = P_2\left(V_3 - V_2\right)$$

$$= 5\times10^5\left(0.05-0.10\right) = -25000\,\text{J}.$$

III. **Step3-1:** heat is then supplied reversibly with the piston firmly locked in position until the pressure rises to the original value of 20 bar.

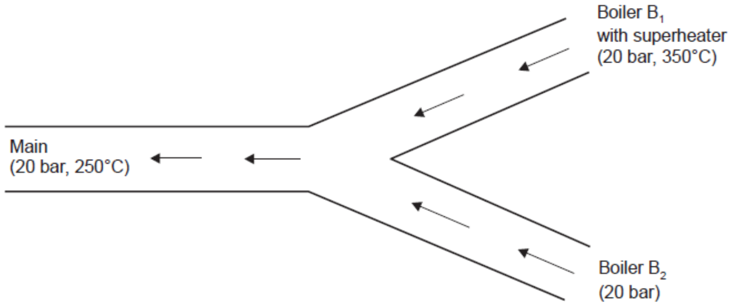
This is an isochoric process in which $W_{31} = 0$.

The net work done during the whole cycle is area 1231

$$W_{1231} = W_{12} + W_{23} + W_{31}$$

$$= 50000 - 25000 + 0 = 25000\,\text{J} = 25\ \text{kJ}..$$

2. (10 marks) Two boilers one with superheater and other without superheater are delivering equal quantities of steam into a common main. The pressure in the boilers and main is 20 bar. The temperature of steam from a boiler with a superheater is 350°C and temperature of the steam in the main is 250°C. Determine the state of steam supplied by the other boiler, and answer the following questions.



a) **(2 marks)** The temperature of B2 is = ____212.42__________ °C.

b) **(2 marks)** The quality of B2 is = _______0.93________.

c) **(2 marks)** The specific enthalpy of Main boiler is = ___2902.5_____ kJ/kg.

d) **(2 marks)** The specific enthalpy of B1 is = _____3137.0______ kJ/kg.

e) **(2 marks)** The specific enthalpy of B2 is = ___2668.0___________ kJ/kg.

We know the state of boiler B1 and main boiler. Consequently, we resort to "superheated" steam tables to obtain that

$$h(20\,\text{bar}, 250^\circ\,\text{C,main boiler}) = 2902.5\,\text{kJ/kg}.$$

$$h(20\,\text{bar}, 350^\circ\,\text{C,B1 boiler}) = 3137.0\ \text{kJ/kg}.$$

To solve for the state of B2, we need to start with energy balance on the system which yields

$$m_{main} h_{main} = m_{B1} h_{B1} + m_{B2} h_{B2}$$

$$m_{main} = m_{B1} + m_{B2}$$

We know that the two boilers produce equal quantities. Using unit flowrate for B1 as basis, the energy balance becomes

$$2h_{main} = h_{B1} + h_{B2}$$

$$h_{B2} = 2h_{main} - h_{B1}$$

$$h_{B2} = 2(2902.5) - 3137 = 2668\,\text{kJ/kg}.$$

Checking this value of enthalpy against the saturated steam tables at 2 MPa, reveals that it falls between the saturated liquid and saturated vapor enthalpies. Therefore, the state of the steam coming from B2 is a mixture of vapor and liquid at 212.42°C. The quality of the stream can be obtained from the general equation for quality

$$2h_{main} = h_{B1} + h_{B2}$$
$$h_{B2} = 2h_{main} - h_{B1}$$
$$h_{B2} = 2(2902.5) - 3137 = 2668 \text{ kJ/kg.}$$
$$x = \frac{h - h_f}{h_g - h_f} = \frac{2668 - 908.79}{2799.5 - 908.79} = 0.93.$$

3. (10 marks, a mark for each question) Choose the most correct answer:

1. **A definite area or space where some thermodynamic process takes place is known as**

a) Thermodynamic system.

b) Thermodynamic cycle.

c) Thermodynamic process.

d) Thermodynamic law.

2. **An open system is one in which**

a) Heat and work cross the boundary of the system, but the mass of the working substance does not.

b) Mass of working substance crosses the boundary of the system but the heat and work do not.

c) Both the heat and work as well as mass of the working substances cross the boundary of the system.

d) Neither the heat and work nor the mass of the working substances cross the boundary of the system.

3. **An isolated system**

a) is a specified region where transfer of energy and/or mass take place.

b) is a region of constant mass and only energy is allowed to cross the boundaries.

c) cannot transfer either energy or mass to or from the surroundings.

d) is one in which mass within the system is not necessarily constant

5) Which of the following is an intensive property of a thermodynamic system?

a) Volume.

b) Temperature.

c) Mass.

d) Energy.

6) When two bodies are in thermal equilibrium with a third body they are also in thermal equilibrium with each other. This statement is called

a) Zeroth law of thermodynamics.

b) First law of thermodynamics.

c) Second law of thermodynamics.

d) Kelvin Planck's law.

7) The temperature at which the volume of a gas becomes zero is called

a) Absolute scale of temperature.

b) Absolute zero temperature.

c) Absolute temperature.

d) None of the above.

8) The value of one bar (in SI units) is equal to ______ N/m^2.

a) 1×10^3 .

b) 1×10^4 .

c) 1×10^5 .

d) 1×10^6.

9) **Which of the following is *correct* ?**
   a) Absolute pressure = gauge pressure + atmospheric pressure.
   b) Gauge pressure = absolute pressure + atmospheric pressure.
   c) Atmospheric pressure = absolute pressure + gauge pressure.
   d) Absolute pressure = gauge pressure – atmospheric pressure.

10) **A series of operations, which take place in a certain order and restore the initial condition is known as**
   a) Reversible cycle.
   b) Irreversible cycle.
   c) Thermodynamic cycle.
   d) None of the above.

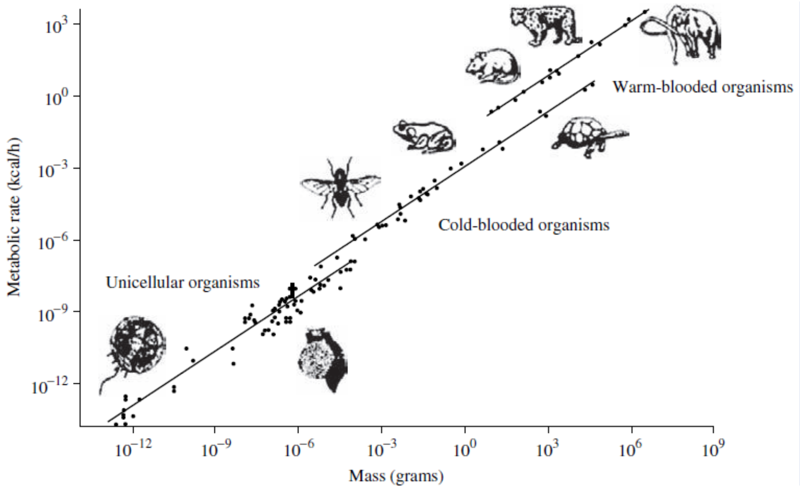
	(A)	(B)	(C)	(D)
01	○	○	○	○
02	○	○	○	○
03	○	○	○	○
04	○	○	○	○
05	○	○	○	○
06	○	○	○	○
07	○	○	○	○
08	○	○	○	○
09	○	○	○	○
10	○	○	○	○

Fill the circles completely.
Don't fill more than one circle for each question. If there are more than one circles filled, you will get a zero for that question.
No answers on the questions sheet will be accepted.
Use a black/blue pen not a pencil.

4. Bonus worth 4 marks out of 30

Everyone has heard about the food chain, but few realize how inefficient it is in nature. The energy conversion efficiency from sunlight to plant growth is only about 1.00%, the energy conversion efficiency of the plants eaten by grazing herbivores is about 20.00% and the energy conversion efficiency of the carnivores that hunt and eat the herbivores is only about 5.00%. If the average daily solar energy reaching the surface of the Earth is 15.3 MJ/d·m^2, then how much land is required to grow the plants needed to feed the herbivores eaten by a large carnivore that requires 10.0 MJ/d to stay alive? What is the overall efficiency of utilization of solar radiation?

Good to know (not part of the question): In 1932, Max Kleiber (1893–1976) published a paper, "Body Size and Metabolism," which included a graph that showed that an animal's metabolic rate scales to the three-quarter power of the animal's mass, or BMR $\propto M^{3/4}$. Kleiber's law has been found to hold across 18 orders of size, from microbes to whales.



Solution

Since our hunting carnivore requires 10.0 MJ of food per day, at a 5.00% food energy conversion rate, it must consume

$$\frac{10.0\ \text{MJ/d}}{0.0500} = 200.\ \text{MJ/d}$$

of herbivore meat. The food energy conversion rate of the grazing herbivores is 20.0%, so they must consume

$$\frac{200.\ \text{MJ/d}}{0.200} = 1000\ \text{MJ/d}$$

in plant food. At a 1.0% energy conversion rate, the plants consumed by the herbivore require

$$\frac{1000\ \text{MJ/d}}{0.0100} = 1.00 \times 10^5\ \text{MJ/d}$$

of solar energy. Since the average solar energy intensity on the surface of the Earth is 15.3 MJ/d · m^2, 100,000 MJ/d of solar energy require an area of

$$\frac{100{,}000\ \text{MJ/d}}{15.3\ \text{MJ/d}\cdot\text{m}^2} = 6540\ \text{m}^2$$

and since 1 acre = 4047 m^2, then

$$6540\ \text{m}^2 \left(\frac{1\ \text{acre}}{4047\ \text{m}^2}\right) = 1.62\ \text{acres}$$

of plant food is required to supply the food chain energy required to meet the 10 MJ/d needs on our carnivore.

Saturated water--Pressure table

Press., p kPa	deg-C Sat. temp., Tsat@p	Spec. Volume m^3/kg Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg Sat. liquid, u_f	Sat. vapor, u_g	Enthalpy, kJ/kg Sat. liquid, h_f	Sat. vapor, h_g	Entropy, kJ/kg*K Sat. liquid, s_f	Sat. vapor, s_g
0.6113	0.01	0.001000	206.14	0	2375.3	0.01	2501.4	0.0000	9.1562
1.0	6.98	0.001000	129.21	29.3	2385.0	29.30	2514.2	0.1059	8.9756
1.5	13.03	0.001001	87.98	54.71	2393.3	54.71	2525.3	0.1957	8.8279
2.0	17.50	0.001001	67.00	73.48	2399.5	73.48	2533.5	0.2607	8.7237
2.5	21.08	0.001002	54.25	88.48	2404.4	88.49	2540.0	0.3120	8.6432
3.0	24.08	0.001003	45.67	101.04	2408.5	101.05	2545.5	0.3545	8.5776
4.0	28.96	0.001004	34.80	121.45	2415.2	121.46	2554.4	0.4226	8.4746
5.0	32.88	0.001005	28.19	137.81	2420.5	137.82	2561.5	0.4764	8.3951
7.5	40.29	0.001008	19.24	168.78	2430.5	168.79	2574.8	0.5764	8.2515
10	45.81	0.001010	14.67	191.82	2437.9	191.83	2584.7	0.6493	8.1502

Units of P changed to MPa

1.00	179.91	0.001127	0.19444	761.68	2583.6	762.81	2778.1	2.1387	6.5865
1.10	184.09	0.001133	0.17753	780.09	2586.4	781.34	2871.7	2.1792	6.5536
1.20	187.99	0.001139	0.16333	797.29	2588.8	798.65	2784.8	2.2166	6.5233
1.30	191.64	0.001144	0.15125	813.44	2591.0	814.93	2787.6	2.2515	6.4953
1.40	195.07	0.001149	0.14084	828.70	2592.8	830.30	2790.0	2.2842	6.4693
1.50	198.32	0.001154	0.13177	843.16	2594.5	844.89	2792.2	2.3150	6.4448
1.75	205.76	0.001166	0.11349	876.46	2597.8	878.50	2796.4	2.3851	6.3896
2.00	212.42	0.001177	0.09963	906.44	2600.3	908.79	2799.5	2.4474	6.3409
2.25	218.45	0.001189	0.08875	933.83	2602.0	936.49	2801.7	2.5035	6.2972
2.50	223.99	0.001197	0.07998	959.11	2603.1	962.11	2803.1	2.5547	6.2575
3.00	233.90	0.001217	0.06668	1004.78	2604.1	1008.42	2804.2	2.6457	6.1869
3.50	242.60	0.001235	0.05707	1045.43	2603.7	1049.75	2803.4	2.7253	6.1253
4	250.40	0.001252	0.04978	1082.31	2602.3	1087.31	2801.4	2.7964	6.0701
5	263.99	0.001286	0.03944	1147.81	2597.1	1154.23	2794.3	2.9202	5.9734

Superheated steam tables (units are the same as in saturated table)

	p = 1.60 Mpa (201.41°C)				p = 1.80 Mpa (207.15°C)				p = 2.00 Mpa (212.42°C)			
T	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	0.12380	2596.0	2794.0	6.4218	0.11042	2598.4	2791.1	6.3794	0.09963	2600.3	2799.5	6.3409
225	0.13287	2644.7	2857.3	6.5518	0.11673	2636.6	2846.7	6.4808	0.10377	2628.3	2835.8	6.4147
250	0.14184	2692.3	2919.2	6.6732	0.12497	2686.0	2911.0	6.6066	0.11144	2679.6	2902.5	6.5453
300	0.15862	2781.1	3034.8	6.8844	0.14021	2776.9	3029.2	6.8226	0.12547	2772.6	3023.5	6.7664
350	0.17456	2866.1	3145.4	7.0694	0.15457	2863.0	3141.2	7.0100	0.13857	2859.8	3137.0	6.9563
400	0.19005	2950.1	3254.2	7.2374	0.16847	2947.7	3250.9	7.1794	0.15120	2945.2	3247.6	7.1271
500	0.2203	3119.5	3472.0	7.5390	0.19550	3117.9	3469.8	7.4825	0.17568	3116.2	3467.6	7.4317
600	0.2500	3293.3	3693.2	7.8080	0.2220	3292.1	3691.7	7.7523	0.19960	3290.9	3690.1	7.7024
700	0.2794	3472.7	3919.7	8.0535	0.2482	3471.8	3918.5	7.9983	0.2232	3470.9	3917.4	7.9487
800	0.3086	3658.3	4152.1	8.2808	0.2742	3657.6	4151.2	8.2258	0.2467	3657.0	4150.3	8.1765
900	0.3377	3850.5	4390.8	8.4935	0.3001	3849.9	4390.1	8.4386	0.2700	3849.3	4389.4	8.3895
1000	0.3668	4049.0	4635.8	8.6938	0.3260	4048.5	4635.2	8.6391	0.2933	4048.0	4634.6	8.5901
1100	0.3958	4253.7	4887.0	8.8837	0.3518	4253.2	4886.4	8.8290	0.3166	4252.7	4885.9	8.7800
1200	0.4248	4464.2	5143.9	9.0643	0.3776	4467.7	5143.4	9.0096	0.3398	4463.3	5142.9	8.9607
1300	0.4538	4679.9	5406.0	9.2364	0.4034	4679.5	5405.6	9.1818	0.3631	4679.0	5405.1	9.1329