Thermodynamics **Test April 15th 2022**

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⟵ Please enter you student number, and write your name above.

NAME, First Name :

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Duration : 2 h - All documents and all calculators authorised - No computer or tablet, no wifi no 4/5G

1 Entropy (2 pts)

Question 1 What is the purpose of the entropy function during a process ?

■ Determine the amount of degraded energy. ■ Determine if the process is possible.
■ Determine the reversibility. □ Determine the heat exchanged.

2 Flow diagram (4 pts)

Question 2 Draw the flow diagram of a petrol car including the role of the electric starter during the start-up phase.

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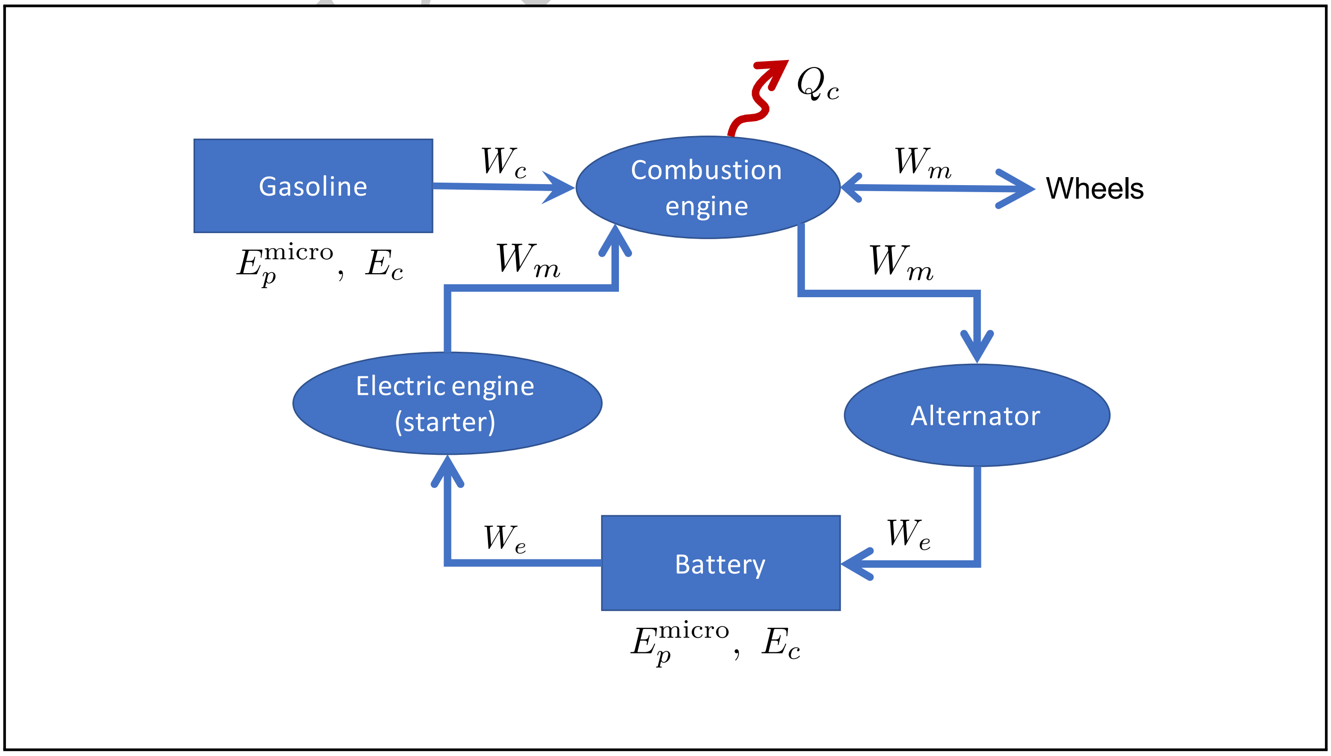

3 Liquid air production (8 pts)

Cryogenic refrigeration is a process used to liquefy gases at very low temperatures. Among the different types of cryogenic refrigeration, the Linde process is used to produce liquid air. This process schematised in the following picture (black and green arrows) is made of the following units :

1) Reversible isothermal compressor
2) Reversible adiabatic compressor
3, 4, 5) Isobaric heat exchangers
6) Expansion valve
7) Gas/liquid separator

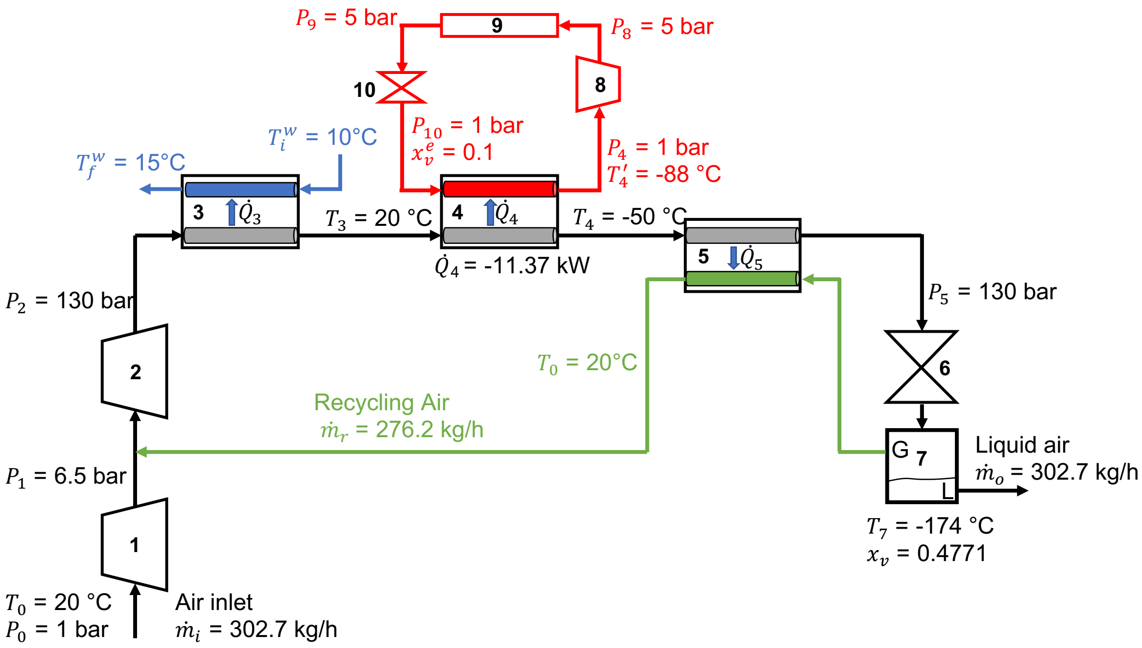

FIGURE 1 – The Linde cycle.

After the first compression (1) the air inlet is mixed with a recycling air flow rate (green arrows) at the same pressure and temperature and then sent to the second compressor. After the second compression (2), the air temperature at the pressure of 130 bar is reduced by using three isobaric heat exchangers. In the first (3) liquid water (blue data) is used to remove heat from the air ; the second (4) uses a refrigerating cycle (red data) to lower the air temperature to $-50\,°C$ and the last (5) uses the recycling air to remove the final heat. A successive expansion valve (6) allow the reduction of the air pressure and temperature inducing the liquefaction of a part of the air. The air moles that remain in the gas phase are 47.71% of the total air moles (vapor fraction $x_v = n_{gas}/n_{tot} = 0.4771$). The following gas/liquid separator (7) allows the separation of the two phases at equilibrium at $-174\,°C$. The liquid air is collected and the remaining gas is used as recycling air in the heat exchanger (5) and then mixed with the inlet air.

3.1 The Linde cycle

Question 3 Give the air temperature immediately after the first compression (in celisus).

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■0 ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9

Question 4 Give the expression of the volumetric flow rate $\dot{V}_1$ immediately after the first compression as a function of $\dot{m}_i$, R, T_0 and P_1 and M_{air} (the molar mass of air).

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The volumetric flow rate is : $\dot{V}_1 = \frac{\Delta V}{\Delta t} = \frac{\Delta n R T_0}{\Delta t P_1} = \frac{\Delta m R T_0}{\Delta t M_{\text{air}} P_1}$, which gives : $\dot{V}_1 = \frac{\dot{m}_i R T_0}{M_{\text{air}} P_1}$

Question 5 Give the volumetric flow rate $\dot{V}_1$ immediately after the first compression (in L/s).

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Question 6 Give the expression of the the air temperature T_2 as a function of T_1, P_1, P_2, C_v and C_p (molar specific heat at constant volume and pressure) immediately after the second compression.

☐ Empty ☐ Wrong ☐ 1 ☐ 2 ■ 3

The air is adiabatically compressed so that $P_1^{1-\gamma} T_1^{\gamma} = P_2^{1-\gamma} T_2^{\gamma}$. The temperature T_2 is : $T_2 = T_1 (P_1/P_2)^{C_v/C_p - 1}$

Question 7 Give the temperature T_2 (in K).

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☐0 ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ■9

Question 8 Give the pressure of the system in the separator (7) (in bar).

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Question 9 Give the expressions of the power $\dot{W}_1$ and $\dot{W}_2$ transferred during the two compressions as a function of T_0, P_0, P_1, P_2, R, C_v, C_p, $\dot{m}_i$, $\dot{m}_r$ and M_{air}.

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Isothermal compression : $W_1 = -\int PdV = -n_1RT\ln(V_1/V_0)$, leading to $\dot{W}_1 = \frac{\dot{m}_iRT}{M}\ln\left(\frac{P_1}{P_0}\right)$

Adiabatic reversible : $W_2 = \Delta U = n_2C_v(T_2 - T_1)$, leading to : $\dot{W}_2 = \frac{\dot{m}_i+\dot{m}_r}{M_{\text{air}}}T_1\left(\left(\frac{P_1}{P_2}\right)^{C_v/C_p-1} - 1\right)$

Question 10 Give the the heat flow rate $\dot{Q}_3$ exchanged in the heat exchangers (3) (in kW).

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Question 11 Give the the heat flow rate $\dot{Q}_5$ exchanged in the heat exchangers (5) (in kW).

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☐0 ☐1 ☐2 ☐3 ☐4 ■5 ☐6 ☐7 ☐8 ☐9
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■0 ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9

Question 12 Give the expression of the mass flow rate $\dot{m}_w$ of liquid water needed in the heat exchanger (3) as a function of T_2, T_3, T_i^w, T_f^w, C_p, C_w (massic heat capacity of liquid water), $\dot{m}_i$, $\dot{m}_r$ and M_{air}.

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In the heat exchanger (3), we have : $\dot{n}_3C_p(T_3-T_2) = \dot{m}_wC_w(T_f^w-T_i^w)$, leading to : $\dot{m}_w = \frac{(\dot{m}_i+\dot{m}_r)C_p(T_3-T_2)}{M_{\text{air}}C_w(T_f^w-T_i^w)}$

Question 13 Give the value of $\dot{m}_w$ (in kg/s).

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■+ | ■0 ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9
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Question 14 Give the expressions of the air temperature T_5 after the final heat exchanger (5) as a function of T_0, T_4, T_7, $\dot{m}_i$ and $\dot{m}_r$.

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In the heat exchanger (5), we have : $\dot{n}_4 C_p(T_5 - T_4) = \dot{n}_r C_p(T_0 - T_7)$, leading to : $T_5 = T_4 + \frac{\dot{m}_r(T_0-T_7)}{\dot{m}_i+\dot{m}_r}$

Question 15 Give the value of T_5 (in celsius).

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☐+	☐0	☐1	☐2	☐3	■4	☐5	☐6	☐7	☐8	☐9
■−	☐0	☐1	☐2	■3	☐4	☐5	☐6	☐7	☐8	☐9

3.2 Refrigerating cycle

The refrigerating cycle uses ethane as refrigerating fluid. The vaporisation of the fluid takes place at −88 °C and 1 bar in the heat exchanger (4) (the cold source) ; once it has become entirely a gas ($\dot{V}'_4 = 13.3$ L/s) it is compressed in an irreversible adiabatic compressor (8) up to a pressure $P_8 = 5$ bar and volumetric flow rate $\dot{V}_8 = 4.34$ L/s. At this pressure the gas is entirely liquefied in the heat exchanger (9) and, finally, the liquid ethane passes through an expansion valve (10) coming back at 1 bar and −88 °C with an amount of 10% of moles in the gas phase (vapor fraction $x_v^e = 0.1$).

Question 16 Give the expression of the COP of the refrigerating cycle as a function of known state variables.

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The COP is by definition : $COP = Q_4/W$, where W is the work of the adiabatic irreversible compressor. We know that $W = -P_8(V_8 - V'_4)$, leading to : $COP = \frac{\dot{Q}_4}{-P_8(\dot{V}_8-\dot{V'}_4)}$

Question 17 Give the value of COP.

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☐0 ☐1 ☐2 ☐3 ☐4 ■5 ☐6 ☐7 ☐8 ☐9

☐0 ☐1 ☐2 ☐3 ■4 ☐5 ☐6 ☐7 ☐8 ☐9

3.3 Thermodynamics data

Air vapor pressure at −174 °C : $p^* = 6.5$ bar, ethane molar mass : $M_{\text{et}} = 30$ g/mol, latent heat of vaporisation of ethane at −88 °C : $L^e_{\text{vap}} = 488$ kJ/kg. specific heat at constant pressure of ethane : $C_p = 52.2$ J/mol/K), specific heat at constant volume of ethane : $C_v = 43.9$ J/mol/K).

4 Problem solving : perspiration (6 pts)

A person is climbing a mountain of 1000 m. His/her body is considered to have a mechanical efficiency of 10% (ratio of mechanical energy produced over the total energy consummed).

Question 18 Assuming his/her body temperature is constant and regulated only through perspiration, determine the mass of water sweat out.

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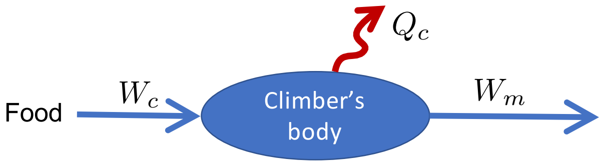
Own the problem :

We define the system as the climber. Let m_w be the mass of evaporated sweat, $m = 90\,\text{kg}$ be the mass of the person, $\eta = 0.1$, the efficiency, $g = 9.91\,\text{m/s}^2$, the gravitational constant, $h = 1000\,\text{m}$, the height to climb, W_m, the work produced by the climber, Q_c, the heat exchanged by the climber, W_c, the energy input of the food, L, the latent heat of evaporation of sweat (assumed to be water), ΔU, $\Delta E_p^{\text{macro}}$, $\Delta E_c^{\text{macro}}$, the variation of internal energy, macroscopic energy and kinetics energy respectively. (1 pts)



(1 pts)

Resolution strategy :

We use the fact that $\eta = -W_m/W_c$ and the first principle of thermodynamics :

$\Delta E_p^{\text{macro}} + \Delta E_k^{\text{macro}} + \Delta U = Q_c + W_m$. (1 pts)

Resolution :

The internal energy of the human body increases thanks to food digestion ($\Delta U = +W_c$). The velocity of the human body remains constant ($\Delta E_k^{\text{macro}} = 0$). We assume that there is no macroscopic potential energy ($\Delta E_p^{\text{macro}} = 0$). We calculate the work of gravitational force : $W_m = -mgh$ and we know that $Q_c = -Lm_w$.

$m_w = \frac{W_c + W_m}{L}$, leading to $m_w = \frac{mgh(1/\eta - 1)}{L}$ (1 pts). N.A. : $m_w = 3.5\,\text{kg}$ (1 pts)

Critical look :

This is a lot of water ! In reality such conditions are encountered only when the wether is so hot (no conduction, no convection), that only perspiration can evacuate the heat produced by the body. (1 pts)