**Thermodynamics** **Test May 26th 2023**

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

NAME, First Name :

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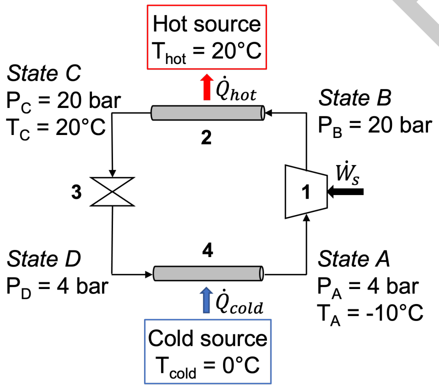
Duration : 2 h - All documents and all calculators authorised - No computer or tablet, no wifi no 4/5G



# Difluoromethane ($CH_2F_2$) : thermodynamic data

Gaseous mass specific heat at constant volume : $\bar{C}_{V(CH_2F_2)} = 0.7056\,\mathrm{J/(gK)}$
Gaseous mass specific heat at constant pressure : $\bar{C}_{P(CH_2F_2)} = 0.8654\,\mathrm{J/(gK)}$
Liquid mass specific heat : $\bar{C}_{(CH_2F_2)} = 2.05\,\mathrm{J/(gK)}$
Enthalpy of vaporisation at $T_{vap,2} = 29\,°\mathrm{C}$ : $\Delta_{\mathrm{vap}}H_{302(CH_2F_2)} = 21\,\mathrm{kJ/mol}$
Enthalpy of vaporisation at $T_{vap,1} = -19\,°\mathrm{C}$ : $\Delta_{\mathrm{vap}}H_{254(CH_2F_2)} = 19.8\,\mathrm{kJ/mol}$
Vapor pressure at $T_{vap,2} = 29\,°\mathrm{C}$ : $P^*_{CH_2F_2} = 20\,\mathrm{bar}$
Vapor pressure at $T_{vap,1} = -19\,°\mathrm{C}$ : $P^*_{CH_2F_2} = 4\,\mathrm{bar}$
Molar mass : $M_{CH_2F_2} = 52\,\mathrm{g/mol}$

## 1 Heat pump for house heating (12 pts)




Nowadays, the need to reduce the global energy consumption is pushing towards new habits in our everyday life. Among them, the use of heat pumps instead of electric radiators for heating of buildings is largely widespread. Let's have a closer look on how a typical heat pump for the heating of an average apartment (around 90 $\mathrm{m}^2$) is made and works. The heat pump cycle is schematised in the picture and is composed of :

- an adiabatic compressor (1) ;
- two heat exchangers (2, 4) ;
- an adiabatic irreversible expansion valve ($\dot{W}_s = 0$).

The fluid employed is difluoromethane ($CH_2F_2$, commercial name R32). It starts the cycle in state $A$ as a gas at 4 bar (mass flowrate $\dot{m}_{(CH_2F_2)} = 121\,\mathrm{kg/h}$) and, after the compression and the successive heat exchange with the apartment (hot source) it arrives to the state $C$ as a liquid. After the expansion, the fluid is in state $D$ as saturated liquid [1] and it goes back to state $A$ by exchanging heat with the external air (cold source). By using the available data in the entire exercise and by clearly explicating your reasoning :

1. A liquid that is about to vaporise (vapour and liquid are at equilibrium).

**Question 1** Give the literal expression of temperature $T_B^{\text{rev}}$ as function of $P_B$, $P_A$, $T_A$, $\bar{C}_{V(\text{CH}_2\text{F}_2)}$ and $\bar{C}_{P(\text{CH}_2\text{F}_2)}$ considering a reversible compression

☐ Vide ☐ 0 ☐ 1 ■ 2

Adiabatic reversible compression (first principle) : $P_A V_A^\gamma = P_B V_B^\gamma$ leading to : $P_A^{1-\gamma} T_A^\gamma = P_B^{1-\gamma} T_B^\gamma$ leading to : $T_B^{\text{rev}} = T_A \left(\frac{P_A}{P_B}\right)^{\frac{\bar{C}_{V(\text{CH}_2\text{F}_2)}}{\bar{C}_{P(\text{CH}_2\text{F}_2)}}-1}$ (1 pts)

**Question 2** What is the numerical value of $T_B^{\text{rev}}$ (in °C) ?

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

**Question 3** Considering from now on that the compression is irreversible and that $T_B^{\text{irrev}} = T_B = 170\,^\circ\text{C}$, give the literal expression of the power $\dot{W}_{s(AB)}$ transferred during the compression as a function of data given in the text.

☐ Vide ☐ 0 ☐ 1 ■ 2

In open systems in steady-state conditions with $\Delta_s \dot{E}_p^M = 0$ and $\Delta_s \dot{E}_k^M = 0$, the first law is $\Delta_s \dot{H} = \dot{Q} + \dot{W}_s$. So in the adiabatic compressor the work is $\dot{W}_{s(AB)} = \Delta_s \dot{H}_{(AB)}$, leading to : $\dot{W}_{s(AB)} = \dot{m}_{(\text{CH}_2\text{F}_2)} \bar{C}_{P(\text{CH}_2\text{F}_2)} (T_B - T_A)$. (1 pts)

**Question 4** What is the numerical value of $\dot{W}_{s(AB)}$ (kW) ?

■ + | ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ■ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9
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**Question 5** Give the literal expression of the rate of heat exchanged $\dot{Q}_{hot}$ with the hot source between states $B$ and $C$ as a function of data given in the text.

□ Vide □ 0 □ 1 □ 2 ■ 3

The gas cools down from $T_B$ to $T_{vap,2}$, becomes liquid and cools down to $T_C$. In heat exchangers the first law is $\dot{Q} = \Delta_s \dot{H}$ leading to :

$$\dot{Q}_{hot} = \dot{m}_{(CH_2F_2)} \bar{C}_{P(CH_2F_2)} \left(T_{vap,2} - T_B\right) - \frac{\dot{m}_{(CH_2F_2)}}{M_{CH_2F_2}} \Delta_{vap} H_{302(CH_2F_2)} + \dot{m}_{(CH_2F_2)} \bar{C}_{(CH_2F_2)} \left(T_C - T_{vap,2}\right)$$

(1.5 pts).

**Question 6** What is the numerical value of $\dot{Q}_{hot}$ (in kW) ?

| Sign | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
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**Question 7** Give the literal expression of the rate of heat exchanged $\dot{Q}_{cold}$ with the cold source between states $D$ and $A$ as a function of data given in the text.

□ Vide □ 0 □ 1 ■ 2

In states $D$, the fluid is at vapour / liquid equilibrium and $T_D = T_{vap,1}$ being $P_D = 4\,\text{bar}$. For heat exchangers $\dot{Q} = \Delta_s \dot{H}$ leading to :

$$\dot{Q}_{cold} = \frac{\dot{m}_{(CH_2F_2)}}{M_{CH_2F_2}} \Delta_{vap} H_{254(CH_2F_2)} + \dot{m}_{(CH_2F_2)} \bar{C}_{P(CH_2F_2)} \left(T_A - T_{vap,1}\right)$$

(1 pts).

**Question 8** What is the numerical value of $\dot{Q}_{cold}$ (in kW) ?

| Sign | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | □ 0 | ■ 1 | □ 2 | □ 3 | □ 4 | □ 5 | □ 6 | □ 7 | □ 8 | □ 9 |
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**Question 9** Give the expression of the real coefficient of performance $CoP_{\text{real}}$ of the heat pump.

☐ Vide ☐ 0 ☐ 1 ■ 2

For heat pumps : $CoP_{\text{real}} = \frac{|\dot{Q}_{hot}|}{\dot{W}_{s(AB)}+\dot{W}_{s(CD)}}$. Being $\dot{W}_{s(CD)}$ nil, $CoP_{\text{real}} = \frac{-\dot{Q}_{hot}}{\dot{W}_{s(AB)}}$ with $\dot{Q}_{hot}$, $\dot{W}_{s(AB)}$ previously reported (1 pts).

**Question 10** What is the numerical value of $CoP_{\text{real}}$ ?

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

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

**Question 11** Give the literal expression of the rate of created entropy $\dot{S}_{cre}$ of the heat pump as a function of data given in the text.

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The system entropy variation over the cycle is nil leading to $\dot{S}_{cre} = \dot{S}_{sys} - \dot{S}_{ex} = -\dot{S}_{ex}$ with $\dot{S}_{ex} = \frac{\dot{Q}_{hot}}{T_{hot}} + \frac{\dot{Q}_{cold}}{T_{cold}}$ leading to :

$$\dot{S}_{cre} = \frac{\dot{m}_{(\mathrm{CH_2F_2})}\bar{C}_{P(\mathrm{CH_2F_2})}\left(T_{vap,2}-T_B\right)-\frac{\dot{m}_{(\mathrm{CH_2F_2})}}{M_{\mathrm{CH_2F_2}}}\Delta_{\text{vap}}H_{302(\mathrm{CH_2F_2})}}{T_{hot}}+$$

$$+\frac{\dot{m}_{(\mathrm{CH_2F_2})}\bar{C}_{(\mathrm{CH_2F_2})}\left(T_C-T_{vap,2}\right)}{T_{hot}}+$$

$$\frac{\frac{\dot{m}_{(\mathrm{CH_2F_2})}}{M_{\mathrm{CH_2F_2}}}\Delta_{\text{vap}}H_{254(\mathrm{CH_2F_2})}+\dot{m}_{(\mathrm{CH_2F_2})}\bar{C}_{P(\mathrm{CH_2F_2})}\left(T_A-T_{vap,1}\right)}{T_{cold}}$$

(2 pts)

**Question 12** What is the numerical value of $\dot{S}_{cre}$ (in J/(K s)) ?

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

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

**Question 13** What is the created entropy rate of the expansion valve (more than one answer is possible) ?

■ $\dot{m}_{(\mathrm{CH_2F_2})}\bar{C}_{(\mathrm{CH_2F_2})}\ln(T_D/T_C)$

☐ $\dot{m}_{(\mathrm{CH_2F_2})}\bar{C}_{P(\mathrm{CH_2F_2})}\ln(T_D/T_C) - (\dot{m}_{(\mathrm{CH_2F_2})}/M_{\mathrm{CH_2F_2}})R\ln(P_D/P_C)$

☐ $\dot{S}_{ex,CD}$

■ $\Delta_s\dot{S}_{CD}$

## 2 Specific heats in ideal gases (3 pts)

An ideal gas (closed system) goes from an initial state $i$ $(P_i, T_i, V_i)$ to a final state $f$ $(P_f, T_f, V_f)$.

**Question 14** By calculating its variation of internal energy and enthalpy due to the transformation from state $i$ to state $f$, demonstrate the relationship $\gamma - 1 = \frac{R}{\bar{C}_{V_m}}$ with $\gamma$ the heat capacity ratio and $\bar{C}_{V_m}$ the molar specific heat at constant volume.

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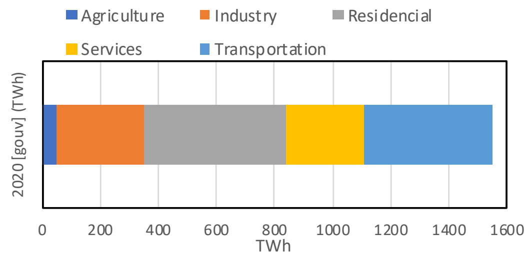
The variation of internal energy and enthalpy of the ideal gas are respectively $\Delta_t U = n\bar{C}_{V_m}(T_f - T_i)$ (0.5 pts) and $\Delta_t H = n\bar{C}_{P_m}(T_f - T_i)$ (0.5 pts). According to the enthalpy definition, we have $\Delta_t H = \Delta_t U + \Delta_t(PV)$ (0.5 pts) which for an ideal gas becomes $\Delta_t H = \Delta_t U + \Delta_t(nRT)$ (0.5 pts) leading to $n\bar{C}_{P_m}(T_f - T_i) = n\bar{C}_{V_m}(T_f - T_i) + nR(T_f - T_i)$. By simplifiyng $n$ and $(T_f - T_i)$ we obtain the Meyer relationship $\bar{C}_{P_m} - \bar{C}_{V_m} = R$ (0.5 pts) which, dividing both members by $\bar{C}_{V_m}$ leads to the wanted relation (0.5 pts).

## 3 Energy consumption drop by electrification of cars (5 pts)

"[Final energy] is the form of energy that we directly use for our needs, such as lighting or heating. It is directly usable without any additional transformation, unlike primary energy (for example, crude oil) that needs to be converted into secondary energy (such as gasoline derived from oil), which in turn needs to be converted into final energy (such as propulsion from gasoline to make the vehicle move). Therefore, from a physical perspective, using energy in the form of electricity rather than in the form of heat reduces our final consumption.

For example, the efficiency of an electric vehicle's motor is around 85%, meaning it converts 85% of the electricity stored in its battery into directly usable energy for propulsion. In contrast, the efficiency is at best only 30% for a thermal vehicle. Based on these assumptions, if all individual vehicles of the future became electric vehicles, we would save nearly 8% of the final energy consumption !

From N. Goldberg, Le Monde (may 3rd 2023)




Final energy consumption in France in 2020 (source : Minist. Trans. Ecol.). In 2020, road accounted for 80% of transport sector consumption. Cars accounted for 60% of road transport consumption.

| Device | Efficiceny |
|---|---|
| Electric engine | $0.85 \pm 0.05$ |
| Gasoline engine | $0.25 \pm 0.05$ |
| Electric power plant* | $0.40 \pm 0.02$ |
| Current transportation | $0.90 \pm 0.05$ |
| Battery | $0.88 \pm 0.02$ |

Efficiency of various devices. * : from gasoline (sources : wiki, sciendo.com, worldbank.org)

**Question 15** Is N. Goldberg right when stating that replacing all cars by electric cars would save 8% of the final energy consumption ? What about primary energy if electricity were generated only by gasoline in electric power plants ?

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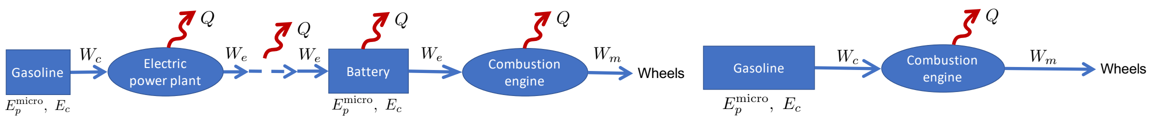
Own the problem : We are given (undefined variables) the fraction of road over total transportation consumption : $f_{\text{road}}$, the fraction of personal car (PC) over road transportation consumption : $f_{\text{PC}}$, the efficiency of electric engine : $\eta^{\text{elec}}$, the efficiency of gasoline engine : $\eta^{\text{gas}}$, the efficiency of electric power plant : $\eta^{\text{power}}$, the efficiency of electricity transportation : $\eta^{\text{trans}}$, the efficiency of batteries : $\eta^{\text{bat}}$, the consumption of primary energy due to PCs : $E^P_{\text{PC}}$, the consumption of final energy due to PCs : $E_{\text{PC}}$, the mechanical work of all PCs : $W_{\text{PC}}$, and the total consumption of final energy : $E_{\text{Tot}}$. Note that prime (') stands for new values when replacing all cars by electric cars (1 pts).

Resolution strategy : (i) For final energy, we are going to calculate the new final energy for PCs and compare the new total final energy to the actual total final energy. (ii) For the primary energy, we are going to compare the primary energy of electric and gasoline cars :




(2 pts)

Resolution : (i) Final energy : for a given mechanical work : $W_{\text{PC}} = \eta^{\text{gas}} E_{\text{PC}} = \eta^{\text{elec}} E'_{\text{PC}}$ (1 pts). We then have : $E'_{\text{Tot}} = (E_{\text{Tot}} - (1 - f_{\text{road}} f_{\text{PC}}) E_{\text{PC}}) + f_{\text{road}} f_{\text{PC}} E'_{\text{PC}}$, leading to : $E'_{\text{Tot}} = (E_{\text{Tot}} - (1 - f_{\text{road}} f_{\text{PC}}) E_{\text{PC}}) + f_{\text{road}} f_{\text{PC}} E_{\text{PC}} \eta^{\text{gas}} / \eta^{\text{elec}}$. The energy saving is then : $(E_{\text{Tot}} - E'_{\text{Tot}})/E_{\text{Tot}} = f_{\text{road}} f_{\text{PC}} E_{\text{PC}} / E_{\text{Tot}} (1 - \eta^{\text{gas}}/\eta^{\text{elec}})$ (1 pts).

From the graph, we read $E_{\text{Tot}} = 1550\,\text{Twh}$ and $E_{\text{PC}} = 440\,\text{TWh}$ leading to $(E_{\text{Tot}} - E'_{\text{Tot}})/E_{\text{Tot}} = (10 \pm 4)\%$. (1 pts)

(ii) Primary energy : for a given mechanical work : $W_{\text{PC}} = \eta^{\text{power}} \eta^{\text{trans}} \eta^{\text{bat}} \eta^{\text{elec}} E'^P_{\text{PC}} = \eta^{\text{gas}} E^P_{\text{PC}}$, leading to energy savings : $(E^P_{\text{Tot}} - E'^P_{\text{Tot}})/E^P_{\text{Tot}} = 1 - \eta^{\text{gas}} / (\eta^{\text{power}} \eta^{\text{trans}} \eta^{\text{bat}} \eta^{\text{elec}})$ (1 pts) leading to : $(E^P_{\text{Tot}} - E'^P_{\text{Tot}})/E^P_{\text{Tot}} = (0 \pm 30)\%$ (1 pts)

Critical look : N. Goldberg is right concerning final energy, but as primary energy is concerned, the balance is nil (at least for the precision of input data we have) (2 pts)