UNIVERSIDADE DE SÃO PAULO

INSTITUTO DE QUÍMICA DE SÃO CARLOS

Operações Unitárias I

Balanço de Energia

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Capacidade calorífica

Fórmula genérica $Cp = f(T) = a + bT + cT^2 + dT^3$

TABELA D e E (pág. 119 e 120) - ANEXO

Líquidos e sólidos $\Rightarrow$ $Cp = Cv$

Gases ideais $\Rightarrow$ $Cp = Cv + R$

Gases reais $\Rightarrow$ muito complexo e não é objetivo deste curso

Cálculo das Entalpias de misturas

$$Cp_m(T) = \sum_{i=1}^{n} y_i Cp_i(T) \qquad \Delta H_m = \int_{T_1}^{T_2} Cp_m(T)\,dT$$

Capacidade calorífica média, $\overline{Cp}$

Entalpia de alguma substância tabelada relativa ao estado de referência

$$\Delta H = \overline{Cp}\,.\Delta T \qquad \Delta H = \overline{Cp}\,.(T - T_{ref})$$

TABELA E

OU

ΔH para a variação entre duas temperaturas T_1 e T_2

$$\Delta H\,(T_1 \rightarrow T_2) = \Delta H(T_2) - \Delta H(T_1) = \overline{Cp}_{T_2}\,(T_2 - T_{ref}) - \overline{Cp}_{T_1}\,(T_1 - T_{ref})$$

Válido porque a entalpia é uma propriedade de estado, ou seja, depende apenas do estado inicial e final do processo.

TABELA D

TABELA D: Capacidade Calorífica

Form 1: C_p(J/mol·°C) or (J/mol·K) $= a + bT + cT^2 + dT^3$
Form 2: C_p(J/mol·°C) or (J/mol·K) $= a + bT + cT^{-2}$

Example: $(C_p)_{[illegible]} = 71.96 + (20.10 \times 10^{-2})T - (12.78 \times 10^{-5})T^2 + (34.76 \times 10^{-9})T^3$, where T is in °C.

Note: The formulas for gases are strictly applicable at pressures low enough for the ideal gas law to apply.

Compound	Formula	Mol. Wt.	State	Form	Temp. Unit	a	$b \cdot 10^3$	$c \cdot 10^5$	$d \cdot 10^9$	Range (Units of T)
Acetone	CH_3COCH_3	58.08	l	1	°C	123.0	18.6			−30–60
			g	1	°C	71.96	20.10	−12.78	34.76	0–120
Acetylene	C_2H_2	26.04	g	1	°C	42.43	6.053	−5.033	18.20	0–120
Air		29.0	g	1	°C	28.94	0.4147	0.3191	−1.965	0–150
			g	1	K	28.09	0.1965	0.4799	−1.965	273–180
Ammonia	NH_3	17.03	g	1	°C	35.15	2.954	0.4421	−6.686	0–120
Ammonium sulfate	$(NH_4)_2SO_4$	132.15	c	1	K	215.9				275–328
Benzene	C_6H_6	78.11	l	1	K	62.55	23.4			279–350
			g	1	°C	74.06	32.95	−25.20	77.57	0–120
Isobutane	C_4H_{10}	58.12	g	1	°C	89.46	30.13	−18.91	49.87	0–12
n-Butane	C_4H_{10}	58.12	g	1	°C	92.30	27.88	−15.47	34.98	0–12
Isobutene	C_4H_8	56.10	g	1	°C	82.88	25.64	−17.27	50.50	0–12
Calcium carbide	CaC_2	64.10	c	2	K	68.62	1.19	-8.66×10^{10}	—	298–72
Calcium carbonate	$CaCO_3$	100.09	c	2	K	82.34	4.975	-12.87×10^{10}	—	273–10
Calcium hydroxide	$Ca(OH)_2$	74.10	c	1	K	89.5				276–37
Calcium oxide	CaO	56.08	c	2	K	41.84	2.03	-4.52×10^{10}		273–11
Carbon	C	12.01	c	2	K	11.18	1.095	-4.891×10^{10}		273–13
Carbon dioxide	CO_2	44.01	g	1	°C	36.11	4.233	−2.887	7.464	0–15
Carbon monoxide	CO	28.01	g	1	°C	28.95	0.4110	0.3548	−2.220	0–15
Carbon tetrachloride	CCl_4	153.84	l	1	K	93.39	12.98			273–34
Chlorine	Cl_2	70.91	g	1	°C	33.60	1.367	−1.607	6.473	0–12
Copper	Cu	63.54	c	1	K	22.76	0.6117			273–135
Cumene (Isopropyl benzene)	C_9H_{12}	120.19	g	1	°C	139.2	53.76	−39.79	120.5	0–12
Cyclohexane	C_6H_{12}	84.16	g	1	°C	94.140	49.62	−31.90	80.63	0–12
Cyclopentane	C_5H_{10}	70.13	g	1	°C	73.39	39.28	−25.54	68.66	0–12
Ethane	C_2H_6	30.07	g	1	°C	49.37	13.92	−5.816	7.280	0–12
Ethyl alcohol (Ethanol)	C_2H_5OH	46.07	l	1	°C	103.1				0
			l	1	°C	158.8				100
			g	1	°C	61.34	15.72	−8.749	19.83	0–12
Ethylene	C_2H_4	28.05	g	1	°C	+40.75	11.47	−6.891	17.66	0–12
Ferric oxide	Fe_2O_3	159.70	c	2	K	103.4	6.711	-17.72×10^{10}	—	273–10
Formaldehyde	CH_2O	30.03	g	1	°C	34.28	4.268	0.0000	−8.694	0–12
Helium	He	4.00	g	1	°C	20.8				All
n-Hexane	C_6H_{14}	86.17	l	1	°C	216.3				20–10
			g	1	°C	137.44	40.85	−23.92	57.66	0–12

TABELA D

Compound	Formula	Mol. Wt.	State	Form	Temp. Unit	a	b · 10^3	c · 10^5	d · 10^9	Range (Units of T)
Hydrogen	H_2	2.016	g	1	°C	28.84	0.00765	0.3288	−0.8698	0–1
Hydrogen bromide	HBr	80.92	g	1	°C	29.10	−0.0227	0.9887	−4.858	0–1
Hydrogen chloride	HCl	36.47	g	1	°C	29.13	−0.1341	0.9715	−4.335	0–1
Hydrogen cyanide	HCN	27.03	g	1	°C	35.3	2.908	1.092		0–1
Hydrogen sulfide	H_2S	34.08	g	1	°C	33.51	1.547	0.3012	−3.292	0–1
Magnesium chloride	$MgCl_2$	95.23	c	1	K	72.4	1.58			273–9
Magnesium oxide	MgO	40.32	c	2	K	45.44	0.5008	−8.732 × 10^10		273–2
Methane	CH_4	16.04	g	1	°C	34.31	5.469	0.3661	−11.00	0–120
			g	1	K	19.87	5.021	1.268	−11.00	273–1
Methyl alcohol (Methanol)	CH_3OH	32.04	l	1	°C	75.86				0
						82.59				40
			g	1	°C	42.93	8.301	−1.87	−8.03	0–7
Methyl cyclohexane	C_7H_{14}	98.18	g	1	°C	121.3	56.53	−37.72	100.8	0–1
Methyl cyclopentane	C_6H_{12}	84.16	g	1	°C	98.83	45.857	−30.44	83.81	0–1
Nitric acid	HNO_3	63.02	l	1	°C	110.0				25
Nitric oxide	NO	30.01	g	1	°C	29.50	0.8188	−0.2925	0.3652	0–3
Nitrogen	N_2	28.02	g	1	°C	29.00	0.2199	0.5723	−2.871	0–1
Nitrogen dioxide	NO_2	46.01	g	1	°C	36.07	3.97	−2.88	7.87	0–1
Nitrogen tetraoxide	N_2O_4	92.02	g	1	°C	75.7	12.5	−11.3		0–3
Nitrous oxide	N_2O	44.02	g	1	°C	37.66	4.151	−2.694	10.57	0–1
Oxygen	O_2	32.00	g	1	°C	29.10	1.158	−0.6076	1.311	0–1
n-Pentane	C_5H_{12}	72.15	l	1	°C	155.4	43.68			0–3
			g	1	°C	114.8	34.09	−18.99	42.26	0–1
Propane	C_3H_8	44.09	g	1	°C	68.032	22.59	−13.11	31.71	0–1
Propylene	C_3H_6	42.08	g	1	°C	59.580	17.71	−10.17	24.60	0–1
Sodium carbonate	Na_2CO_3	105.99	c	1	K	121				288–3
Sodium carbonate decahydrate	$Na_2CO_3 \cdot 10H_2O$	286.15	c	1	K	535.6				298
Sulfur	S	32.07	c (Rhombic)	1	K	15.2	2.68			273–3
			c (Monoclinic)	1	K	18.3	1.84			368–3
Sulfuric acid	H_2SO_4	98.08	l	1	°C	139.1	15.59			10–4
Sulfur dioxide	SO_2	64.07	g	1	°C	38.91	3.904	−3.104	8.606	0–1
Sulfur trioxide	SO_3	80.07	g	1	°C	48.50	9.188	−8.540	32.40	0–1
Toluene	C_7H_8	92.13	l	1	°C	148.8				0
			l	1	°C	181.2				100
			g	1	°C	94.18	38.00	−27.86	80.33	0–1
Water	H_2O	18.016	l	1	°C	75.4				0–1
[illegible]			g	1	°C	33.46	0.6880	0.7604	−3.593	0–1

TABELA E:Capacidade Calorífica Média de Gases Combustíveis Ideais: Unidades em SI.

	$\bar{C}_p$(J/mol·°C) Reference state: P_{ref} = 1 atm, T_{ref} = 25°C						
T(°C)	Air	O_2	N_2	H_2	CO	CO_2	H_2O
0	28.94	29.24	29.03	28.84	29.00	36.63	33.55
25	29.05	29.39	29.06	28.84	29.06	37.15	33.63
100	29.21	29.80	29.16	28.86	29.23	38.63	33.92
200	29.45	30.32	29.32	28.90	29.47	40.45	34.34
300	29.71	30.80	29.52	28.95	29.72	42.10	34.80
400	29.97	31.24	29.74	29.03	29.99	43.59	35.29
500	30.25	31.65	29.98	29.12	30.27	44.93	35.81
600	30.53	32.02	30.24	29.23	30.56	46.14	36.36
700	30.81	32.39	30.51	29.35	30.85	47.23	36.92
800	31.10	32.71	30.79	29.48	31.14	48.20	37.49
900	31.38	33.02	31.07	29.63	31.42	49.07	38.08
1000	31.65	33.30	31.34	29.78	31.70	49.85	38.66
1100	31.92	33.55	31.62	29.94	31.97	50.54	39.24
1200	32.18	33.79	31.88	30.12	32.23	51.18	39.81
1300	32.42	34.02	32.13	30.29	32.47	51.75	40.37
1400	32.65	34.23	32.37	30.47	32.69	52.28	40.91
1500	32.85	34.42	32.58	30.66	32.89	52.77	41.42

ᵃ Calculated from the heat capacity formulas of Table D

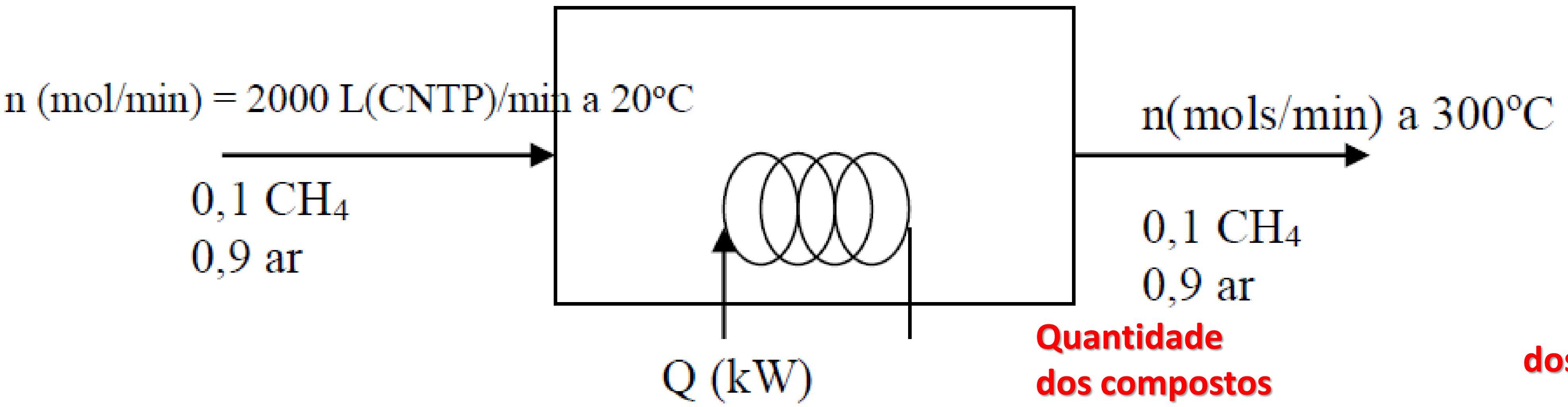
Example: The enthalpy of oxygen at 700°C relative to O_2 at 25°C [or the enthalpy change for the process $O_2(25°C) \rightarrow O_2(700°C)$] is

$$\hat{H}_{O_2}(700°C) = (\bar{C}_p)_{700°C}(700°C - 25°C)$$
$$= \left(32.39 \frac{J}{mol \cdot °C}\right)(675°C) = 21\,860 \text{ J/mol}$$

TABELA E

$$H = Cp_T.(T-T_{ref})$$

Exercício III.6) Uma corrente contendo 10% CH_4 e 90% de ar em volume deve ser aquecida de 20 a 300°C. Calcule a taxa de calor requerida em kW se a vazão volumétrica do gás é $2{,}00 \times 10^3$ L (CNTP)/min



- **Metano (CH_4) => Simples**
- **Ar => mistura**

$$Q = \Delta H = \sum_{\text{saída}} n_i H_i - \sum_{\text{entrada}} n_i H_i$$

Quantidade dos compostos (n_i)

Natureza dos compostos (H_i)

TABELA E

TABELA E: Capacidade Calorífica Média de Gases Combustíveis Ideais: Unidades em SI.

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T(°C)	Air	O_2	N_2	H_2	CO	CO_2	H_2O
0	28.94	29.24	29.03	28.84	29.00	36.63	33.55
25	29.05	29.39	29.06	28.84	29.06	37.15	33.63
100	29.21	29.80	29.16	28.86	29.23	38.63	33.92
200	29.45	30.32	29.32	28.90	29.47	40.45	34.34
300	29.71	30.80	29.52	28.95	29.72	42.10	34.80
400	29.97	31.24	29.74	29.03	29.99	43.59	35.29
500	30.25	31.65	29.98	29.12	30.27	44.93	35.81
600	30.53	32.02	30.24	29.23	30.56	46.14	36.36
700	30.81	32.39	30.51	29.35	30.85	47.23	36.92
800	31.10	32.71	30.79	29.48	31.14	48.20	37.49
900	31.38	33.02	31.07	29.63	31.42	49.07	38.08
1000	31.65	33.30	31.34	29.78	31.70	49.85	38.66
1100	31.92	33.55	31.62	29.94	31.97	50.54	39.24
1200	32.18	33.79	31.88	30.12	32.23	51.18	39.81
1300	32.42	34.02	32.13	30.29	32.47	51.75	40.37
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Example: The enthalpy of oxygen at 700°C relative to O_2 at 25°C [or the enthalpy change for the process $O_2(25°C) \rightarrow O_2(700°C)$] is

$$\hat{H}_{O_2}(700°C) = (\bar{C}_p)_{700°C}(700°C - 25°C)$$
$$= \left(32.39 \frac{J}{mol \cdot °C}\right)(675°C) = 21\,860 \text{ J/mol}$$