**UNIVERSIDADE DE SÃO PAULO**

**INSTITUTO DE QUÍMICA DE SÃO CARLOS**

*Operações Unitárias I*

# Balanço de Energia

# AULA 15

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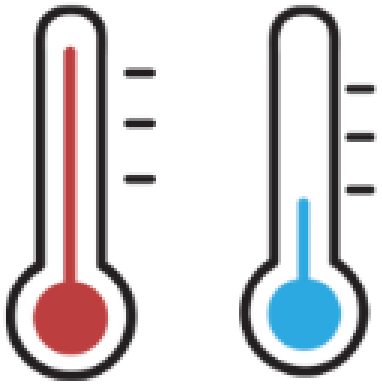
# Operações com Mudança de Fase

## Calor sensível

Provoca variação na temperatura



$$Q = m \cdot c \cdot \Delta\theta$$

## Calor latente

Provoca alteração no estado físico

$$Q = m \cdot L$$

# OPERAÇÕES COM MUDANÇA DE FASE

## 1) Calor latente de vaporização ($\Delta H_v$)

Calor requerido para vaporizar uma quantidade unitária de líquido a T e P constantes.

## 2) Calor latente de fusão ($\Delta H_m$)

Calor requerido para fundir uma quantidade unitária de sólido a T e P constantes.

## 3) Calor latente de sublimação ($\Delta H_s$)

Calor requerido para vaporizar uma quantidade unitária de sólido a T e P constantes.

# Operações com Mudança de Fase


Água (S) 0 ºC ----------- > Água (L) 0 ºC ----------> Água (L) 100 ºC ----- > Água (V) 100 ºC

**ΔHf** **ΔH sensível** **ΔHv**

**Exercício III.7)** Uma mistura equimolar de benzeno (B) e tolueno (T) a 10°C é alimentada continuamente a um vaso no qual a mistura é aquecida a 50°C a uma pressão de 34,8 mmHg. O produto líquido contém 40% B molar e o produto vapor contém 68,4% B molar. Quanto calor deve ser transferido à mistura por mol de alimentação?

Dados: $(\Delta H_v)_B$ (80,10°C) = 30,765 kJ/mol

$(\Delta H_v)_T$ (110,62 °C) = 33,47 kJ/mol

**Calor latente**

- ✓ Processo contínuo
- ✓ Regime permanente
- ✓ Base de cálculo => 1 mol

# 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:* $(C_p)_{\text{ammonia (g)}} = 71.96 + (20.10 \times 10^{-3})T - (12.78 \times 10^{-5})T^2 + (34.76 \times 10^{-9})T^3$, 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 | $a$ | $b \cdot 10^2$ | $c \cdot 10^5$ | $d \cdot 10^9$ | 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 | $(NH_4)_2SO_4$ | | | | | | | | | |
| 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 | $C_4H_{10}$ | | | | | | | | | |
| *n*-Butane | $C_4H_{10}$ | 58.12 | g | 1 | °C | 92.30 | 27.88 | −15.47 | 34.98 | 0–12[illegible] |
| Isobutene | $C_4H_8$ | 56.10 | g | 1 | °C | 82.88 | 25.64 | −17.27 | 50.50 | 0–12[illegible] |
| Calcium carbide | $CaC_2$ | 64.10 | c | 2 | K | 68.62 | 1.19 | $-8.66 \times 10^{10}$ | — | 298–72[illegible] |
| Calcium carbonate | $CaCO_3$ | 100.09 | c | 2 | K | 82.34 | 4.975 | $-12.87 \times 10^{10}$ | — | 273–10[illegible] |
| Calcium hydroxide | $Ca(OH)_2$ | 74.10 | c | 1 | K | 89.5 | | | | 276–37[illegible] |
| Calcium oxide | CaO | 56.08 | c | 2 | K | 41.84 | 2.03 | $-4.52 \times 10^{10}$ | | 273–11[illegible] |
| Carbon | C | 12.01 | c | 2 | K | 11.18 | 1.095 | $-4.891 \times 10^{10}$ | | 273–13[illegible] |
| Carbon dioxide | $CO_2$ | 44.01 | g | 1 | °C | 36.11 | 4.233 | −2.887 | 7.464 | 0–15[illegible] |
| Carbon monoxide | CO | 28.01 | g | 1 | °C | 28.95 | 0.4110 | 0.3548 | −2.220 | 0–15[illegible] |
| Carbon tetrachloride | $CCl_4$ | 153.84 | l | 1 | K | 93.39 | 12.98 | | | 273–34[illegible] |
| Chlorine | $Cl_2$ | 70.91 | g | 1 | °C | 33.60 | 1.367 | −1.607 | 6.473 | 0–12[illegible] |
| 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 | $-17.72 \times 10^{10}$ | — | 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 |
| Hydrogen | H | | | | | | | | | |

# TABELA D

| Compound | Formula | Mol. Wt. | State | Form | Temp. Unit | a | $b \cdot 10^{2}$ | $c \cdot 10^{5}$ | $d \cdot 10^{9}$ | 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 | $-8.732 \times 10^{10}$ | | 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 (Rhombic) | c | 1 | K | 15.2 | 2.68 | | | 273–3 |
| | | (Monoclinic) | c | 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 |
| [illegible] | [illegible] | [illegible] | 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 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Water | $H_2O$ | 18.016 | l | 1 | °C | 75.4 | | | | 0–1 |
| [illegible] | [illegible] | [illegible] | g | 1 | °C | 33.46 | 0.6880 | 0.7604 | −3.593 | 0–1 |