University of Jordan
Chemical Engineering Department
Chemical Engineering Thermodynamics (1) – 905322

Lecture 17: Refrigeration, Liquefaction, and Mechanical Explosions

Dr. Ali Khalaf Al-Matar

Outline

- Refrigeration
  - Importance of refrigeration
  - Refrigerators and Refrigerants
  - Analysis
- Liquefaction
  - Simple Liquefaction
  - Linde Liquefactions
- Mechanical Explosions
  - TNT Equivalents
  - Vapor Phase Explosions
  - BELEVE Explosions

د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Importance of Refrigeration

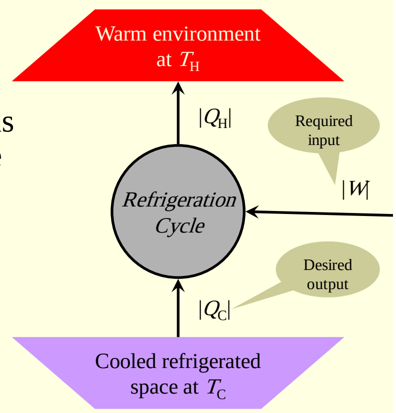
د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية، aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

- Air conditioning (AC).
- Treatment, transportation and preservation of foods and beverages.
- Dehydration of gases.
- Production of ice.
- Air distillation.
- Lubricating-oil purification.
- Low temperature reactions.
- Separation of volatile hydrocarbons.
- Biomedical.

Refrigeration Terminology

د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية، aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

- A **refrigerator** is a device which removes heat from a low temperature region to a high temperature region.
- The **objective of a refrigerator** is to maintain the refrigerated space at low temperature by discarding and/or removing heat from it.
- A **refrigerant** is the working fluid used in the refrigeration cycle.



Refrigeration Efficiency

- A **ton of refrigeration** is the equivalent of heat removal rate at 211 kJ/min (200 Btu/min).
- Efficiency in refrigeration is defined in terms of coefficient of performance COP.

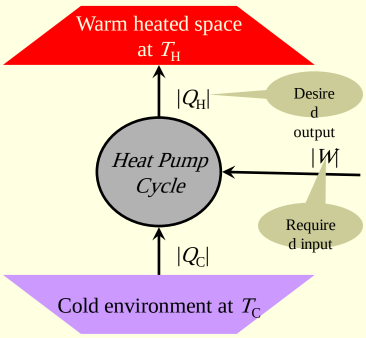
$$\mathrm{COP_R} = \frac{\text{Desired output}}{\text{Required input}} \geq 0$$

$$\mathrm{COP_R} = \frac{|Q_C|}{|W|} = \frac{1}{|Q_H|/|Q_C|-1} = \frac{1}{T_H/T_C-1} \geq 0 \qquad (1)$$

د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الاردنية aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Carnot Heat Pump

- A device that transfers heat from a low T medium to a high T medium.
- The objective of a heat pump is to supply heat into the warmer space.
- Efficiency is defined in terms of coefficient of performance COP.



$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} \geq 1$$

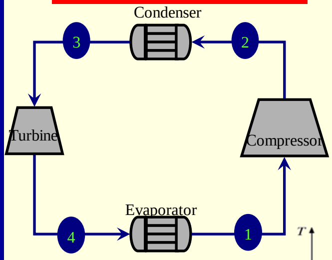
$$\mathrm{COP_{HP}} = \frac{|Q_H|}{|Q_H|-|Q_C|} = \frac{1}{1-|Q_C|/|Q_H|} = \frac{1}{1-T_C/T_H} \geq 1 \qquad (2)$$

د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الاردنية aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

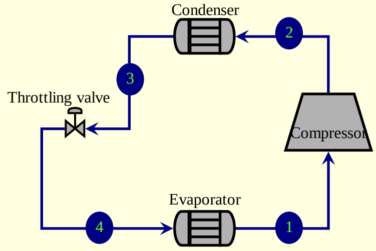
Rankine & Vapor Compression Cycles

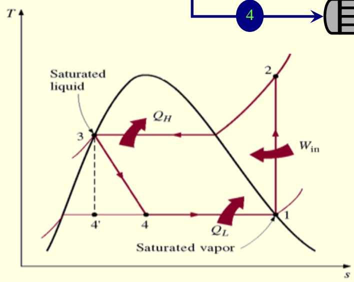
aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Rankine Refrigerator



Vapor Compression Refrigerator





Rankine & Vapor Compression Cycles II

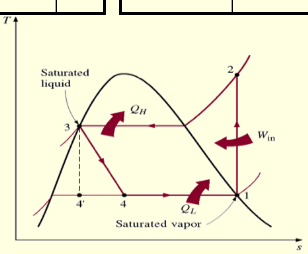
aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Rankine Refrigerator

Turbine	Sat. L to V-L (3→4)	Isentropic	W_T
Evaporator	V-L to Sat. V	Isothermal-Isobaric	Q_H
Compressor	Sat. V to Superheated V.	Isentropic	W_C
Condenser	Superheated V. to Sat. L.	Isobaric	Q_C

Vapor Compression Refrigerator

Throttling valve	Sat. L to V-L	Isenthalpic	0
Evaporator	V-L to Sat. V	Isothermal-Isobaric	Q_H
Compressor	Sat. V to Superheated V.	Isentropic	W_C
Condenser	Superheated V. to Sat. L.	Isobaric	Q_C



Refrigeration Efficiency

- COP for the Rankine cycle

$$\mathrm{COP_R} = \frac{Q_{\mathrm{Evaporor}}}{W_{\mathrm{Compressor}} + W_{\mathrm{Turbine}}} = \left| \frac{\underline{H}_1 - \underline{H}_4}{(\underline{H}_2 - \underline{H}_1) + (\underline{H}_4 - \underline{H}_3)} \right| \quad (3)$$

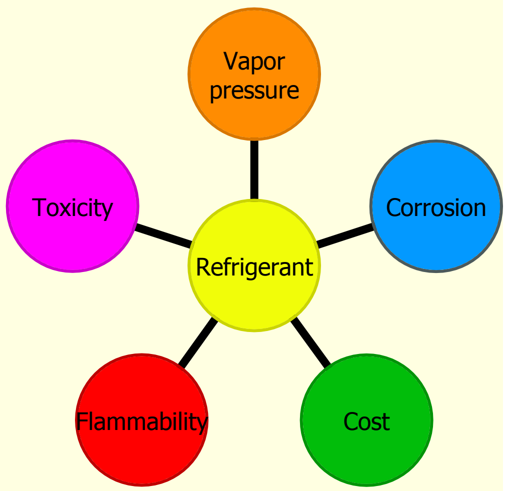
- COP for the ideal vapor compression cycle

$$\mathrm{COP_R} = \frac{Q_{\mathrm{Evaporor}}}{W_{\mathrm{Compressor}}} = \left| \frac{\underline{H}_1 - \underline{H}_4}{\underline{H}_2 - \underline{H}_1} \right| \quad (3')$$

aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

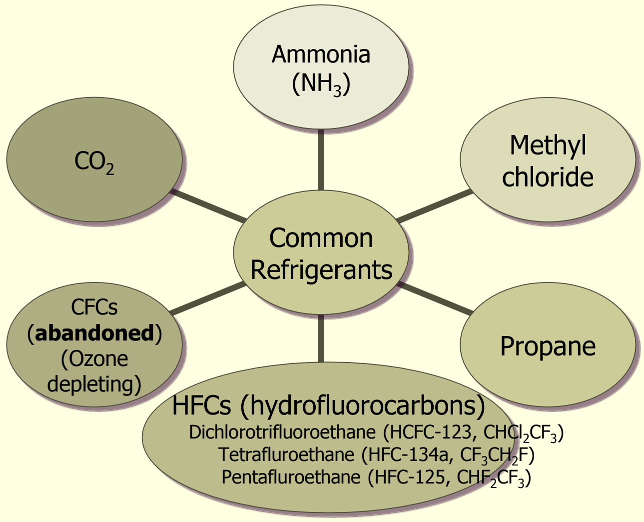
Choice of Refrigerant

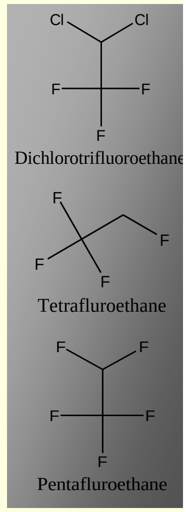
- The COP of the Carnot refrigerator is independent of the type of refrigerant used.
  - Not true for real refrigerators due to inherent irreversibilities.



aalmatar@ju.edu.jo
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Common Refrigerants





aalmatar@ju.edu.jo
د. علي خلف المطر، قسم الهندسة الكيماوية، الجامعة الأردنية
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Liquefaction

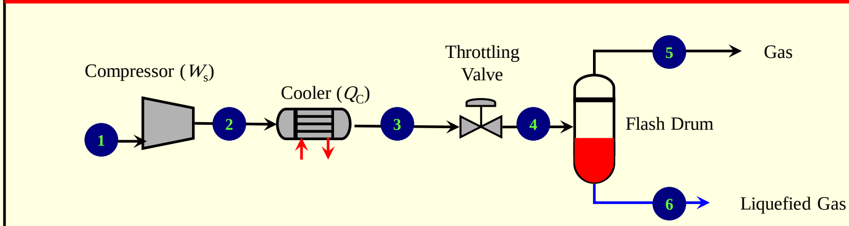
- Liquefaction is the process by which gases are liquefied.
- Important in many areas e.g., Liquefied Natural Gas (LNG), and refrigerant gases.
- Two different approaches for liquefaction:
  - Cool the gas down to below its boiling-point temperature at the desired pressure
    - not practical due to cooling requirements.
  - **Compress** the gas to high $P \rightarrow$ **cool** at the same $P \rightarrow$ **expand** to low P and T using **Joule-Thompson** expansion.

$$\eta_{\text{Liquefaction}} = \frac{\text{Amount of liquefied gas produced}}{\text{Work done in the compressor}}$$

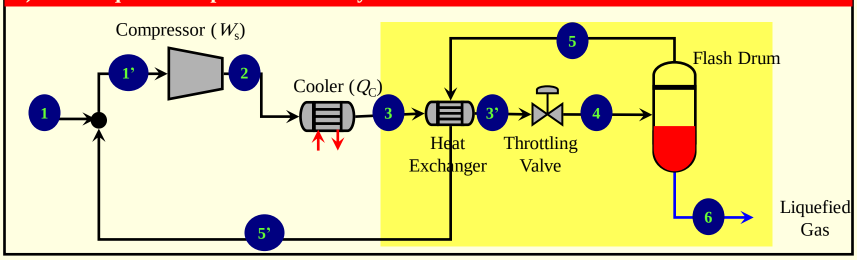
aalmatar@ju.edu.jo
د. علي خلف المطر، قسم الهندسة الكيماوية، الجامعة الأردنية
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Simple and Linde Liquefaction

a) Simple liquefaction process without recycle.



b) Linde liquefaction process with recycle.



aalmatar@ju.edu.jo ، د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

Linde Process Calculations

- Use the **heat exchanger**, **throttle valve** and **flash drum** as a system
  - Mass balance

$$M_3 = M_{5'} + M_6$$

  - Energy balance

$$M_3 \underline{H}_3 = M_{5'} \underline{H}_{5'} + M_6 \underline{H}_6$$

  - Solve for the liquid fraction *x*.

- Base the flow on 1 kg to the compressor

$$M_{1'} = 1; \quad M_{5'} = 1 - x; \quad M_1 = x$$

- Find the enthalpy at the compressor inlet

$$\underline{H}_{1'} = M_{5'} \underline{H}_{5'} + M_1 \underline{H}_1$$

- Find compressor work using the isentropic conditions (multistage & intercooling?)

$$W = \underline{H}_2 - \underline{H}_{1'}$$

aalmatar@ju.edu.jo ، د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية
Ali Al-Matar, Chemical Engineering Dept., University of Jordan

aalmatar@ju.edu.jo د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية
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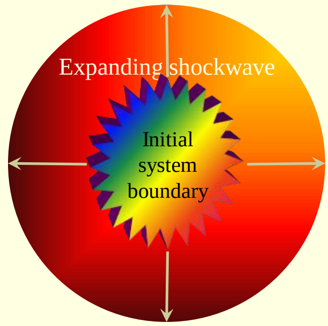
Mechanical Explosions

- **Explosions that occur without reaction**.
  - Bursting of an overpressurized tank.
  - Rapid depressurization of a hot liquid that leads to partial flashing.
- Explosions
  - **Very rapid** that there is no heat or mass transfer to/from the surroundings to the exploding material.
  - The exploding material undergoes a **rapid (and uniform) expansion**, pushing away the surrounding air.



shockwave speed

M < 1 **Deflagration**

M = 1 **Explosion**

aalmatar@ju.edu.jo د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية
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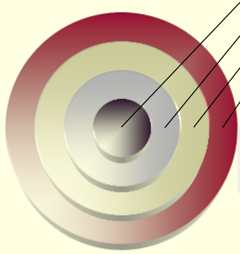
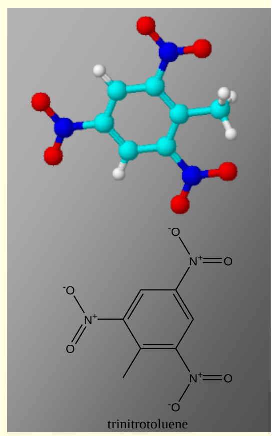
Explosion Equivalents

- Trinitrotoluene (TNT) is the standard to measure explosions against.
  - Blast energy = 4600 kJ/kg.



R = 7 m. Total destruction.
R = 14 m. Substantial damage.
R = 55 m. Minor damage.
R = 130 m. Shattered windows.

Damage classification for the explosion of 5.0 kg TNT.



Vapor-Phase Explosions

- Assumptions: closed system, isentropic

Energy balance

$$W = M[\hat{U}(T_f, P = \text{ambient}) - \hat{U}(T_i, P_i)] \quad (4)$$

Entropy balance

$$\hat{S}(T_f, P = \text{ambient}) = \hat{S}(T_i, P_i) \quad (5)$$

- Ideal gas case (V_S is the initial system volume)

$$T_f = T_i \left(\frac{P = \text{ambient}}{P_i} \right)^{R/C_P^*} \quad (6)$$

$$-W = \frac{P_i V_S}{\gamma - 1} \left[1 - \left(\frac{P = \text{ambient}}{P_i} \right)^{(\gamma-1)/\gamma} \right] \quad (7)$$

aalmatar@ju.edu.jo
د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية
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Boiling Liquid Evaporating Vapor Explosions (BLEVEs)

- A compressed liquid or Liquid-Vapor mixture undergoing sudden depressurization may partially or completely vaporize.

Energy balance

$$\begin{aligned} W &= M[X_f \hat{U}^{\text{V}}(T_f, P = \text{ambient}) + (1 - X_f)\hat{U}^{\text{L}}(T_f, P = \text{ambient})] \\ &\quad - M[X_i \hat{U}^{\text{V}}(T_i, P_i) + (1 - X_i)\hat{U}^{\text{L}}(T_i, P_i)] \end{aligned} \quad (8)$$

Entropy balance

$$\begin{aligned} X_f \hat{S}^{\text{V}}(T_f, P = \text{ambient}) &+ (1 - X_f)\hat{S}^{\text{L}}(T_f, P = \text{ambient}) \\ &= X_i \hat{S}^{\text{V}}(T_i, P_i) + (1 - X_i)\hat{S}^{\text{L}}(T_i, P_i) \end{aligned} \quad (9)$$

aalmatar@ju.edu.jo
د. علي خلف المطر، قسم الهندسة الكيميائية، الجامعة الأردنية
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Simplified BELEVE Analysis

- Estimate the vapor fraction and the energy released from only knowledge of specific heat of liquid and the latent heat of vaporization.

Energy released

$$-W = M\left[C_P^L(T_i - T_b) - X_f\left(\Delta\hat{H}^{\text{vap}} - \frac{RT}{MW}\right)\right] \qquad (10)$$

Final vapor fraction

$$X_f = 1 - \exp\left[\frac{C_P^L}{\Delta\hat{H}^{\text{vap}}}(T_b - T_i)\right] \qquad (11)$$

aalmatar@ju.edu.jo
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