How are power generation (refrigeration cycles implemented in practice? 

**Ideal Gas Heat Engines**

(not practical, but instructional to analyze)

\[ T_H \rightarrow W \rightarrow T_C \]

\[ 1 \rightarrow 2 \text{ expansion, } T_H \]
\[ 2 \rightarrow 3 \text{ adiab. compression} \]
\[ 3 \rightarrow 4 \text{ isoth. } T_C \]
\[ 4 \rightarrow 1 \text{ adiab. compression} \]

When analyzed using adiabatic ideal gas expressions + 1st law balances (see Example 4.1)

\[ \eta = \frac{-W}{Q_H} = \frac{TH - TC}{TH} \]

Theoretical maximum (Carnot) efficiency

\[ \therefore \text{ Ideal-gas } T \text{ is the same as Carnot } T \]

\[ \Rightarrow \text{ Thermodynamic Temperature } \]
Practical issues preventing implementation:
* Isothermal turbines/compressors cannot be constructed
* Need huge equipment sites (low p of T6.)
* Cost of compression

**Rankine Cycle**

Practical power generation using a working fluid (usually steam). Industrial revolution.

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**Example 4.2**

Steam, \( T_H = 800 K, \ T_C = 373 K \) \( \eta = ? \)

Start from point 3, saturated vapor @ \( T_C = 373 K \)

From Webbook: \( P_3 = P_4 = 1 \text{ bar} \) \[ h_3 = 48.2 \frac{kJ}{mol} \] \[ s_3 = 13.5 \frac{J}{mol K} \]

Saturation T calc.: \[ h_4 = 7.5 \frac{kJ}{mol} \] \[ s_4 = 23.5 \frac{J}{mol K} \]

Adiabatic expansion is in the best case - isentropic, \( s_2 = s_3 \). From \( T_2 = 800 K \) (calc.) we can obtain \( P_2 = 27.4 \text{ bar} \) \( h_2 = 63.4 \frac{kJ}{mol} \)
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The pumping step \( 4 \rightarrow 1 \) also operates at best isentropically, so that: \( S_1 = S_4 = 23.5 \frac{J}{mol \cdot K} \); from isobaric calculation at \( p_1 = p_2 = 27.4 \) bar:

\[ T_1 = 373 \text{ K (no T change)} \quad h_1 = 7.6 \text{ kJ/mol} \]

\[ \Delta h = h_1 - h_4 = 0.1 \text{ kJ/mol} \quad \text{(very small)} \]

\[ \Delta h = h_3 - h_2 = -15.2 \text{ kJ/mol} \]

\[ h = 15.2 \text{ kJ} = 55.8 \text{ kJ/mol} \]

Compare to \( \eta_{rev} = \frac{800 - 373}{800} = 53\% \)

Why is efficiency lower? \( \rightarrow \) Non-isothermal operation of boiler

Refrigeration Cycles

Slight modification of "reversed" Rankine Cycle:

\begin{itemize}
  \item \( 3 \rightarrow 4 \) \quad \text{evaporator}
  \item \( 4 \rightarrow 1 \) \quad \text{expansion valve (throttling)}
  \item \( 1 \rightarrow 2 \) \quad \text{adiabatic compr.}
  \item \( 2 \rightarrow 3 \) \quad \text{condenser}
\end{itemize}

E.g. Car air conditioner w/ R134a (Example 4.3)

\[ \theta_4 = 130 \text{ °F}, \quad \theta_1 = \theta_2 = 40 \text{ °F} \]
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From the NIST WebBook, saturation properties of R134a @ 40 °F, vapor: $h_2 = 401 \text{ kJ/kg}$ $s_2 = 1.72 \text{ kJ/(kg K)}$

Point 3 has $s_3 = s_2$

At $T_4 = 130 °F$, sat. liquid $\Rightarrow p_4 = 14.7 \text{ bar, } h_4 = 279 \text{ kJ/kg}$

Isobaric calculation at $p_3 = p_4$ to match the value of the entropy (1.72 kJ/(kg K)) gives:

$T_3 = 137 °F$, $h_3 = 430 \text{ kJ/kg}$

Throttling value is isenthalpic, $h_1 = h_4$

$\dot{w} = h_3 - h_2 = 29 \text{ kJ/kg}$ $\dot{Q}_c = h_2 - h_1 = 122 \text{ kJ/kg}$

$\frac{\dot{Q}_c}{\dot{w}} = 4.2$

Compare to Carnot: $\frac{T_c}{T_4 - T_c} = 5.6$

With the use of two 3-way valves, the role of cold + hot coil can be reversed and an air conditioner can operate as a heat pump, bringing heat into a building from the outside (cooler) air.