Hydrogen and fuel cells

Hydrogen compression

Draft 2024

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Hydrogen as a gas

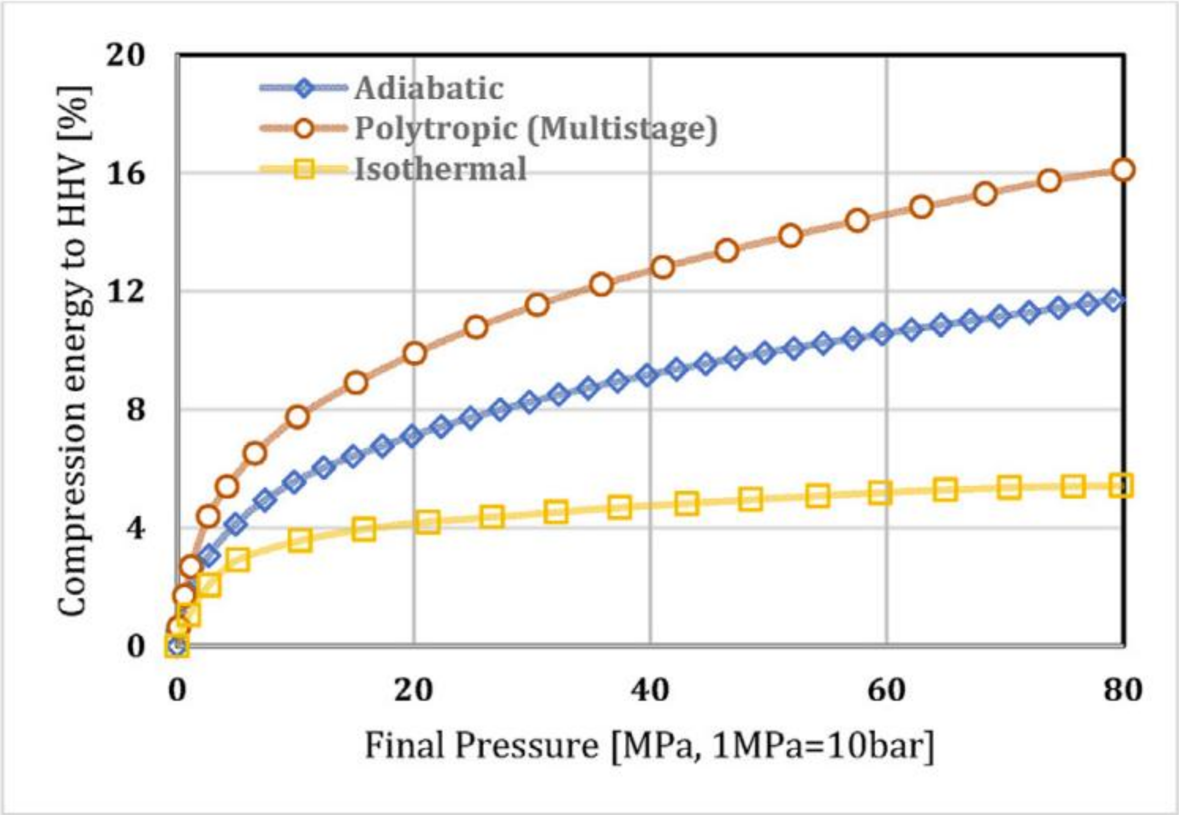

Fig. 5 – Energy required for the compression of hydrogen compared to its higher heating value, HHV [17].

M.V. Lototskyy a,*, V.A. Yartys b,c,**, B.G. Pollet a, R.C. Bowman Jr

Metal hydride hydrogen compressors: A review,

international journal of hydrogenenergy39(2014)5818-5851

Hydrogen as a gas

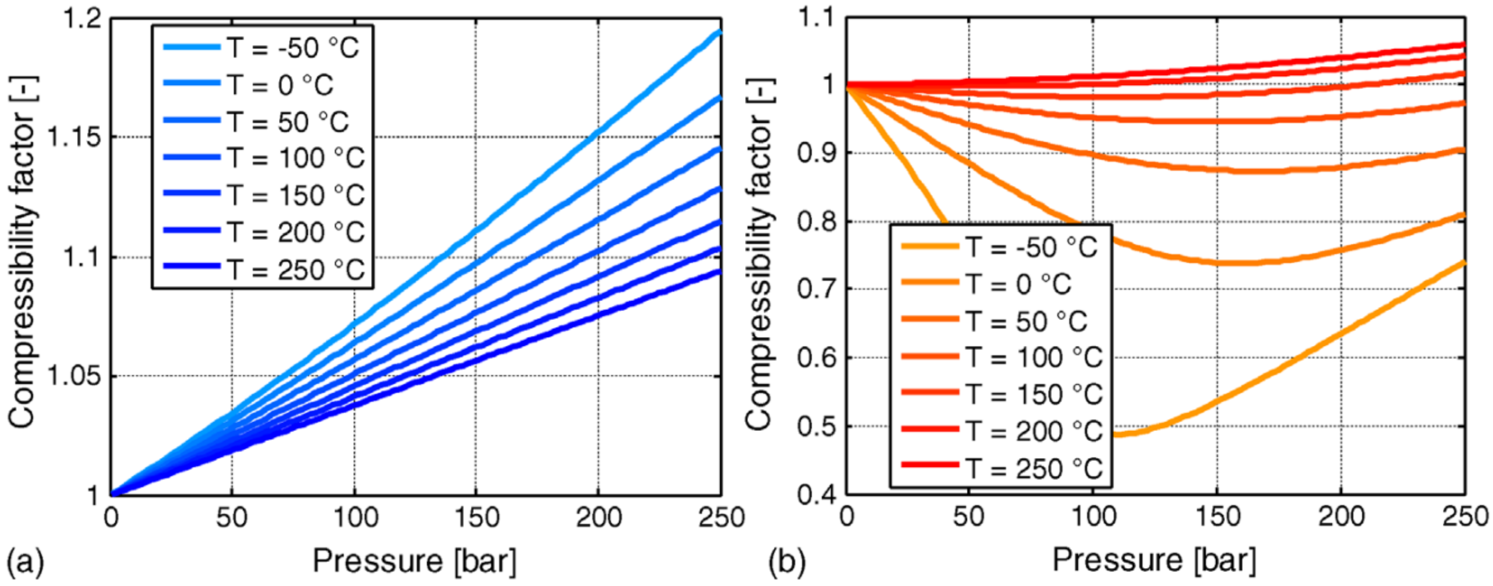

Figure 25.1 Compressibility factor of hydrogen (a) and methane (b).

M.V. Lototskyy a,*, V.A. Yartys b,c,**, B.G. Pollet a, R.C. Bowman Jr

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Hydrogen as a gas

- The compressibility factor of hydrogen is above, and that of methane below, 1 at ambient temperature conditions and pressures below 250 bar. The meaning of this can be best explained with the help of a sample calculation. A storage tank with a geometric volume of 1 m3, temperature of 20 °C, and a pressure of 250 bar contains 18 kg hydrogen or 194 kg methane when the compressibility factor is taken into account. However, under ideal gas assumption it contains 21 kg hydrogen and 165 kg of methane. Consequently, the mass stored in the tank is underestimated by 18% in the case of methane and overestimated by 14% in the case of hydrogen when using the ideal gas law.

Hydrogen as a gas

$$w_{t,12} = \int_{1}^{2} v \, \mathbf{d}p$$

Indirect method

$$w_{t,12} = (h_2 - h_1) - q_{12}$$

Direct method

Hydrogen as a gas

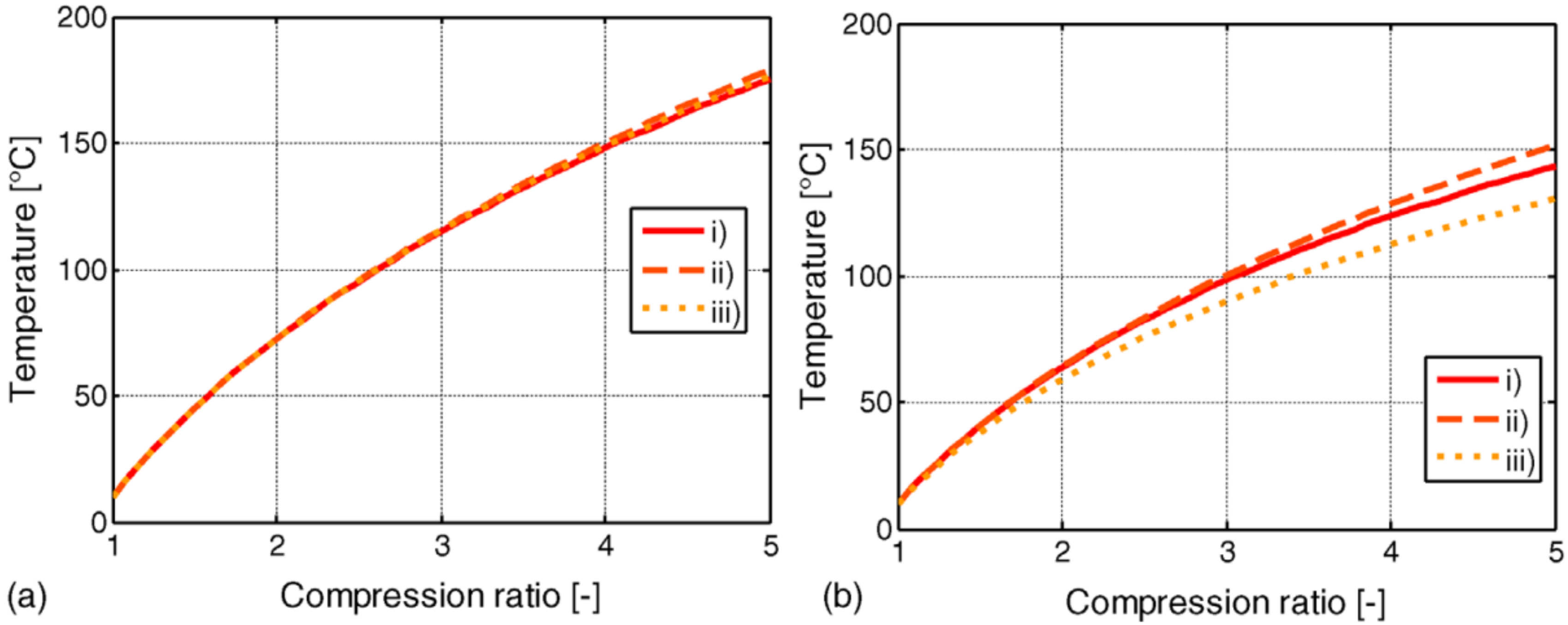

Figure 25.6 Temperature of hydrogen (a) and methane (b) after isentropic compression as a function of the compression ratio for different calculation methods: (i) direct method, real gas, (ii) indirect method, real gas, and (iii) indirect method, ideal gas.

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Hydrogen as a gas

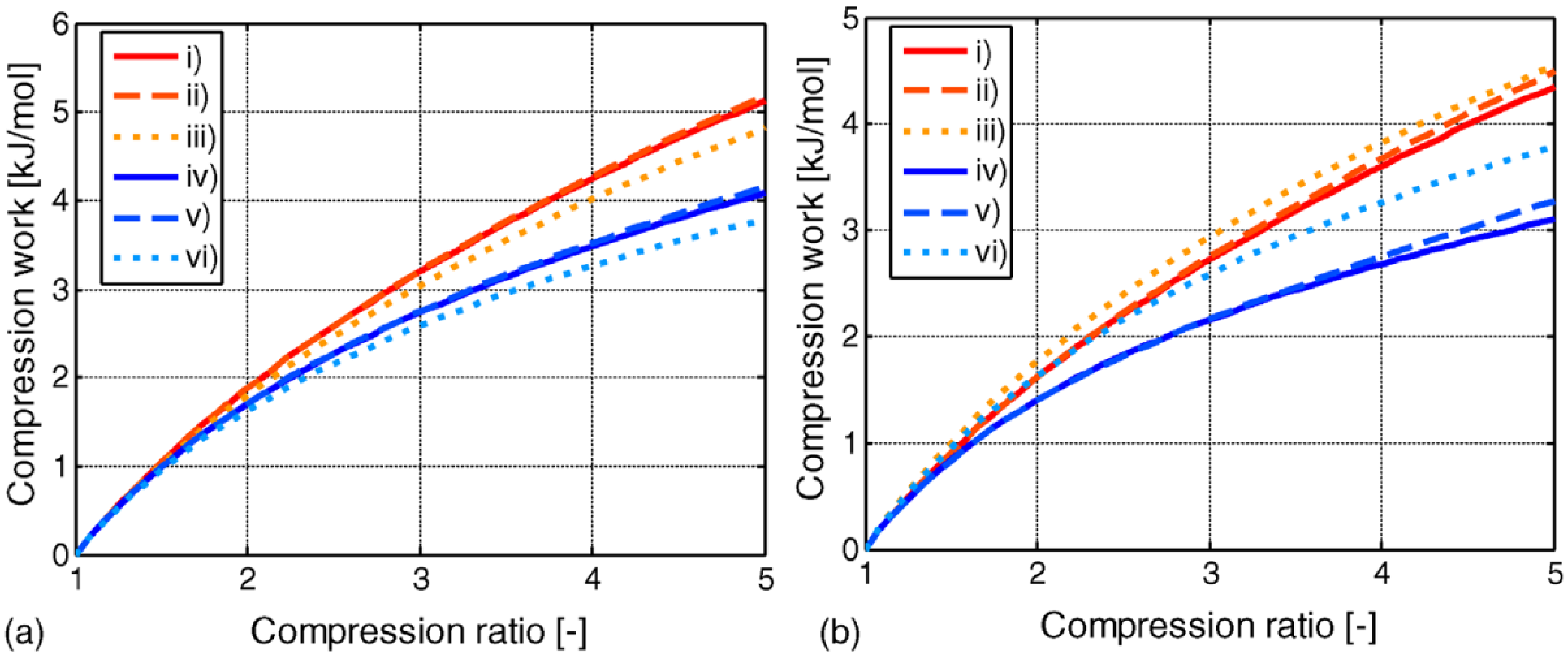

Figure 25.5 Compression work of hydrogen (a) and methane (b) as a function of the compression ratio for different processes and calculation methods: (i) isentropic process, direct method, real gas; (ii) isentropic process, indirect method, real gas; (iii) isentropic process, indirect method, ideal gas; (iv) isothermal process, direct method, real gas; (v) isothermal process, indirect method, real gas; (vi) isothermal process, indirect method, ideal gas.

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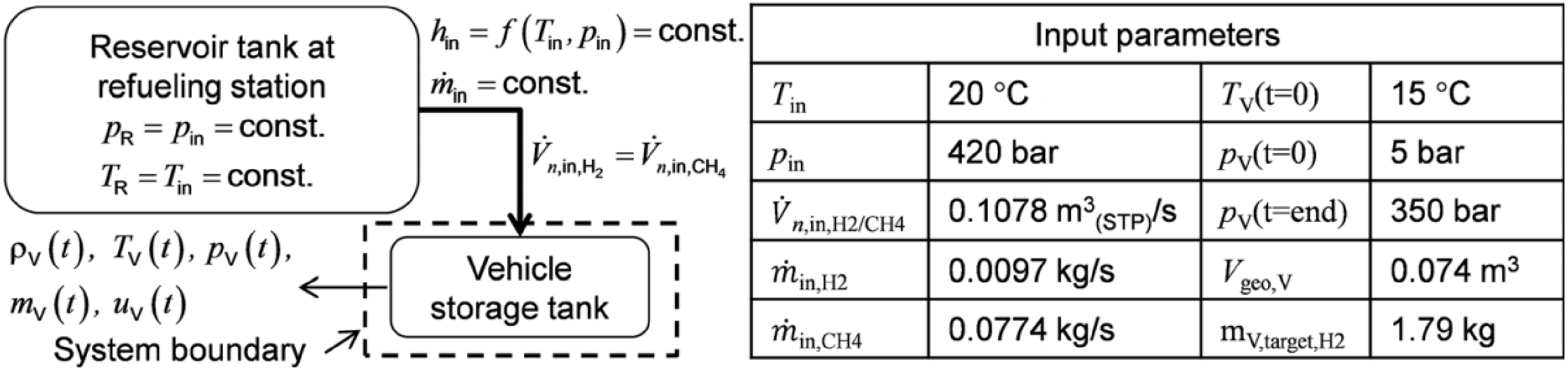
Example refuelling station



Input parameters			
T_{in}	20 °C	$T_V(t=0)$	15 °C
p_{in}	420 bar	$p_V(t=0)$	5 bar
$\dot{V}_{n,in,H2/CH4}$	0.1078 $m^3_{(STP)}/s$	$p_V(t=end)$	350 bar
$\dot{m}_{in,H2}$	0.0097 kg/s	$V_{geo,V}$	0.074 m^3
$\dot{m}_{in,CH4}$	0.0774 kg/s	$m_{V,target,H2}$	1.79 kg

Figure 25.8 Schematic diagram and input parameters of the refueling process example.

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Example refuelling station

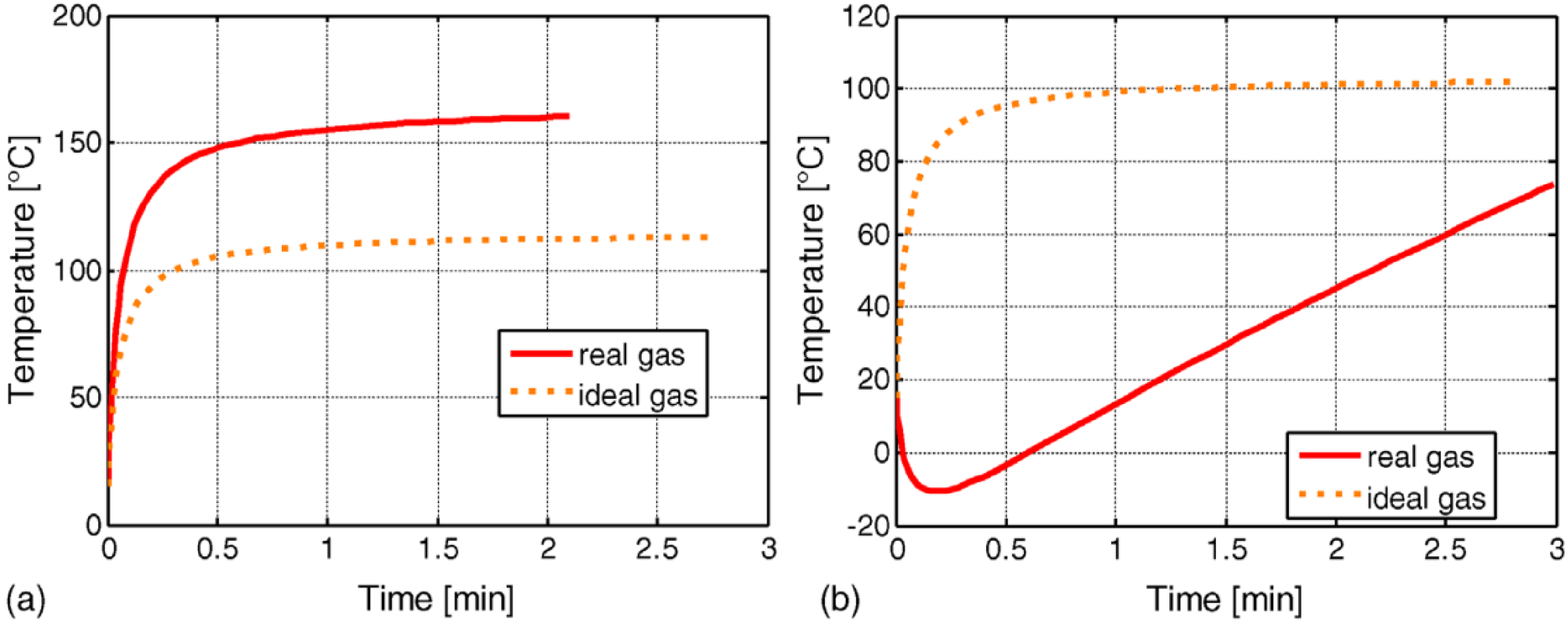

Figure 25.9 Temporal variation of the storage tank temperature of hydrogen (a) and methane (b).

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Example refuelling station

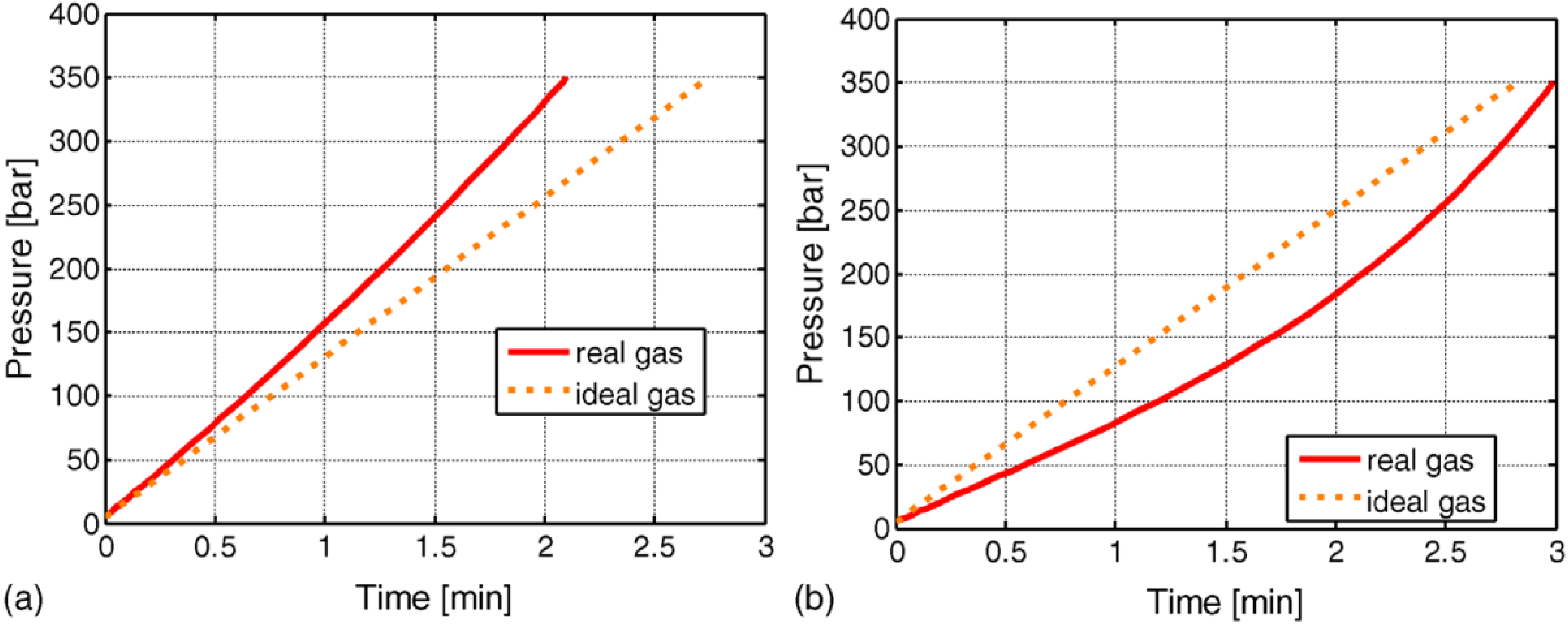

Figure 25.10 Temporal variation of the storage tank pressure of hydrogen (a) and methane (b).

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Example salt cave

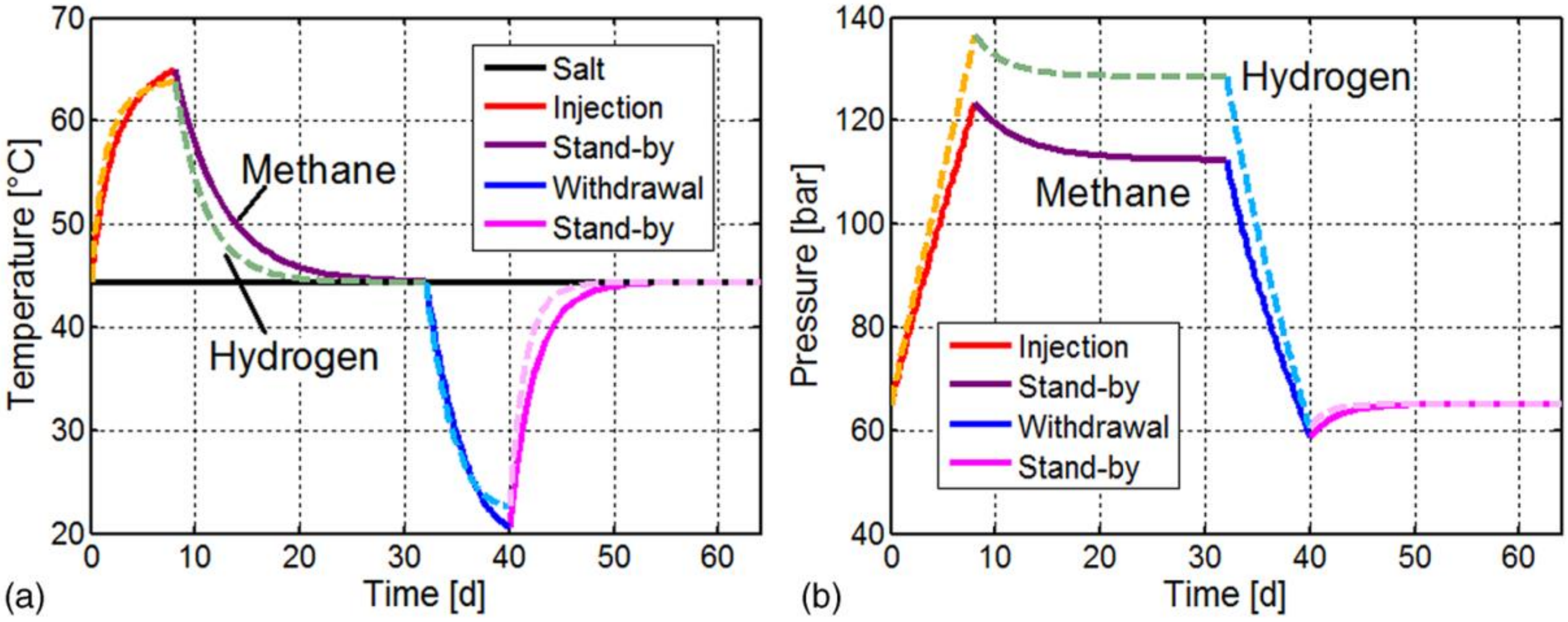

Figure 25.12 Temporal variation of the cavern temperature (a) and pressure (b) of hydrogen and methane.

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Example salt cave

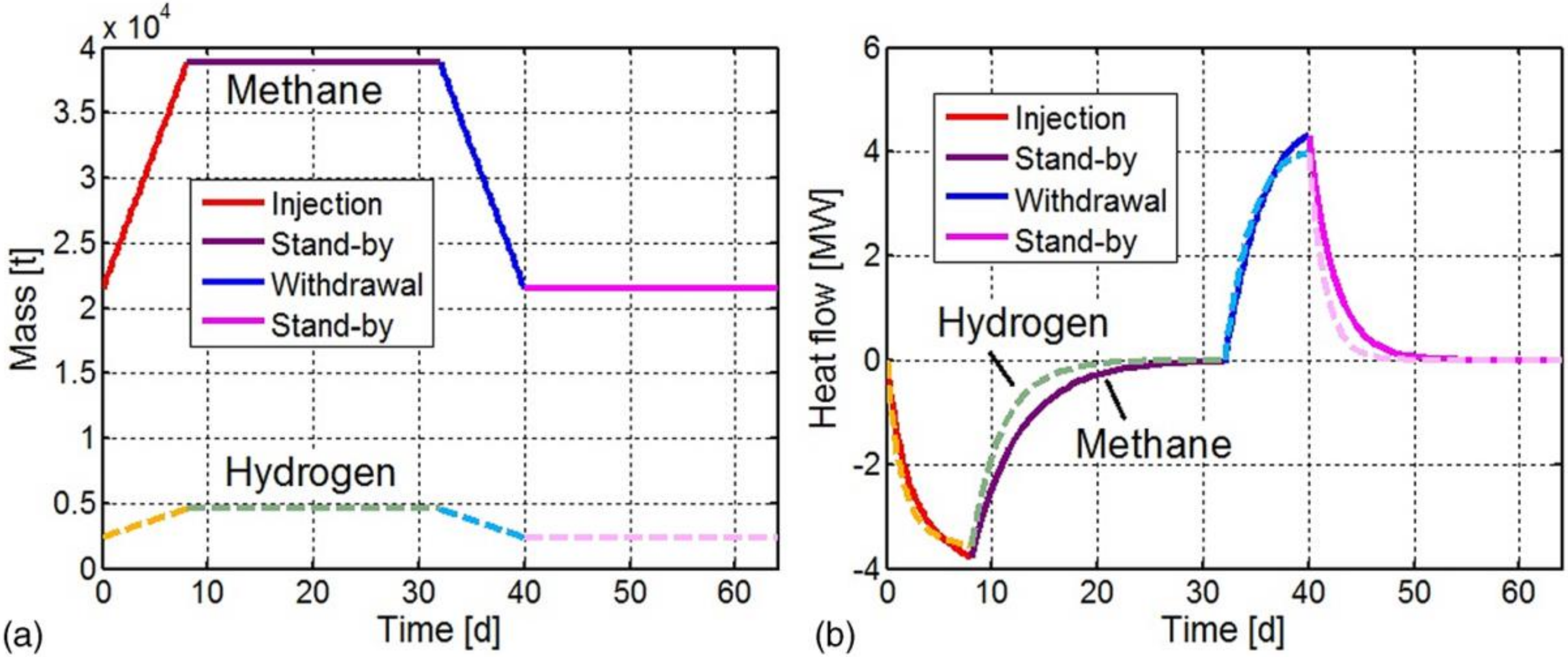

Figure 25.13 Temporal variation of the stored mass (a) and the heat flow (b) of hydrogen and methane.

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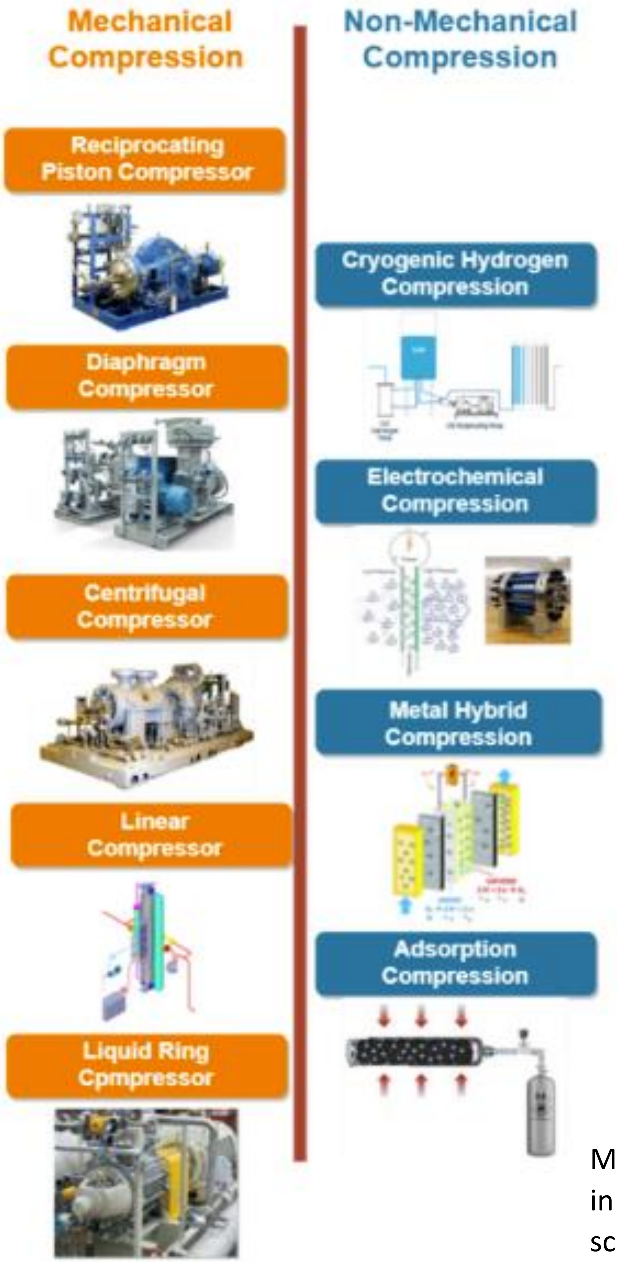

Fig. 12 — Classification of the available hydrogen compression technologies, adapted from Ref. [41].

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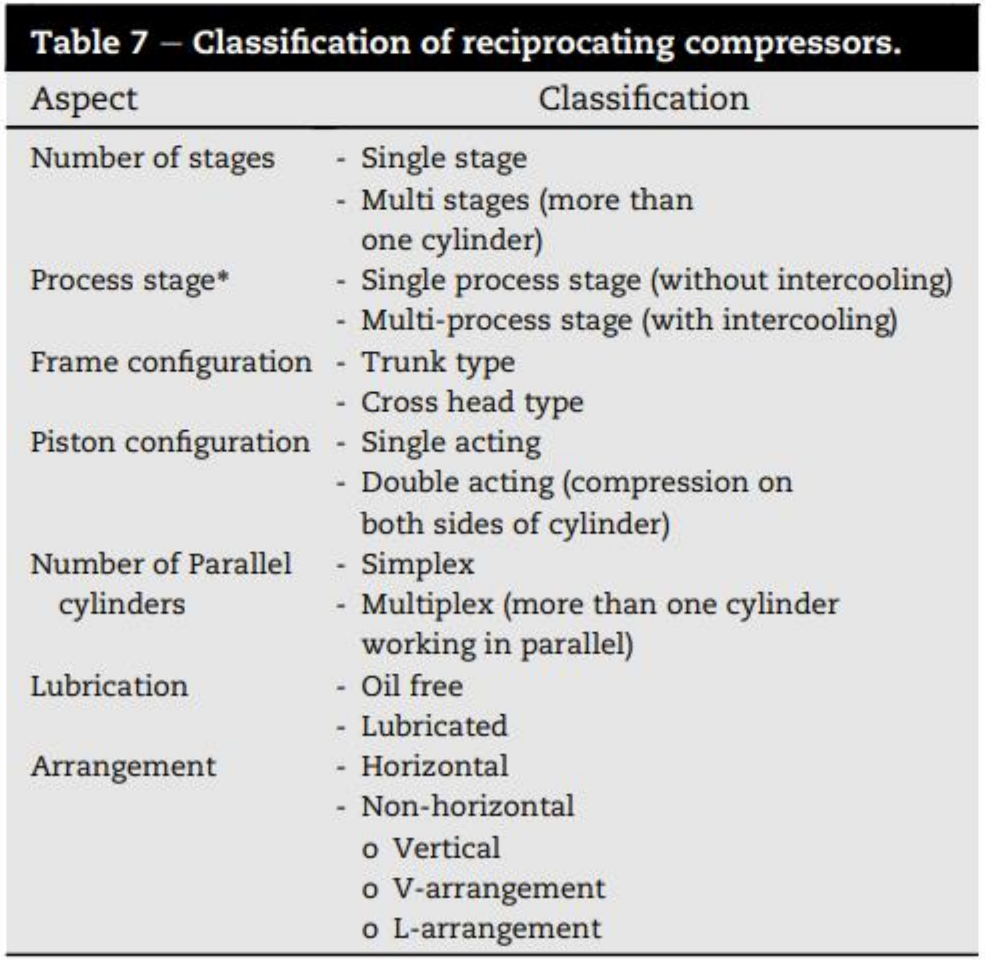

Table 7 – Classification of reciprocating compressors.

Aspect	Classification
Number of stages	- Single stage - Multi stages (more than one cylinder)
Process stage*	- Single process stage (without intercooling) - Multi-process stage (with intercooling)
Frame configuration	- Trunk type - Cross head type
Piston configuration	- Single acting - Double acting (compression on both sides of cylinder)
Number of Parallel cylinders	- Simplex - Multiplex (more than one cylinder working in parallel)
Lubrication	- Oil free - Lubricated
Arrangement	- Horizontal - Non-horizontal o Vertical o V-arrangement o L-arrangement

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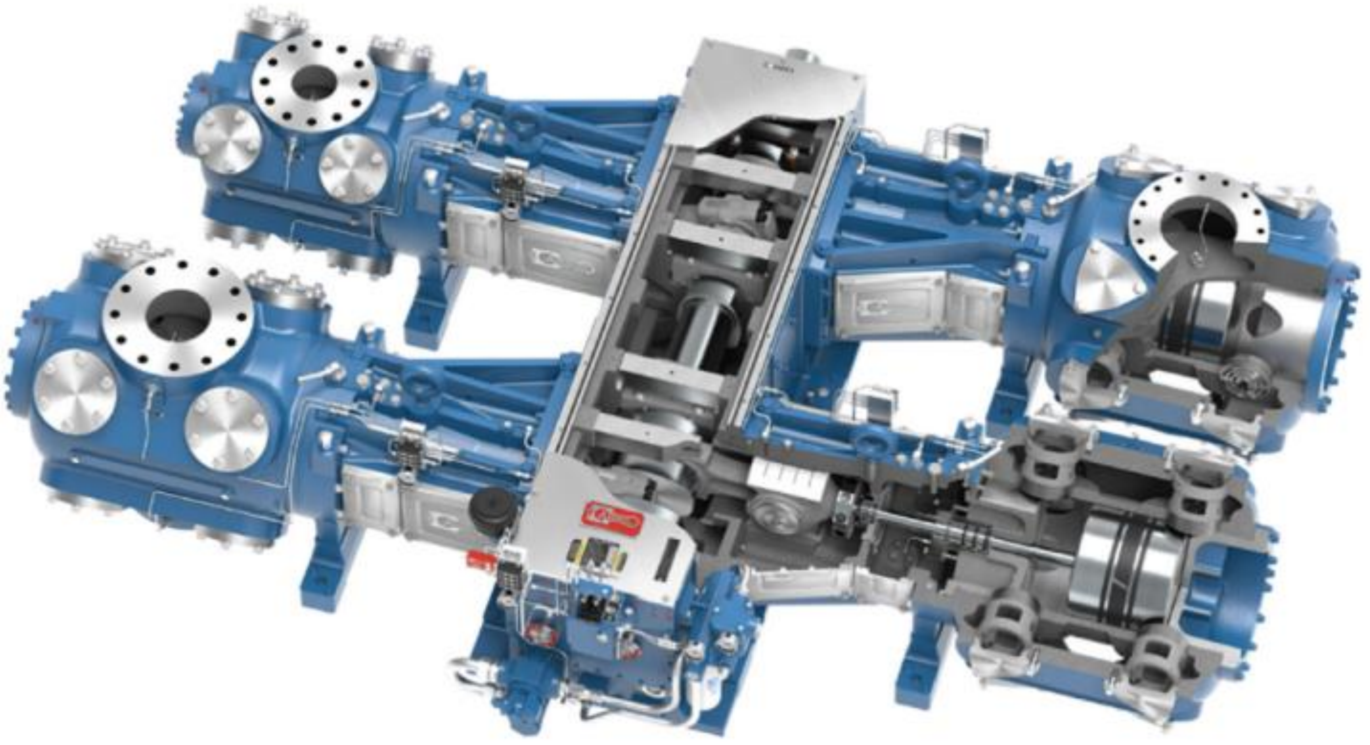

Fig. 13 – An example of a large size horizontal-type reciprocating compressor, courtesy of Arielcorp

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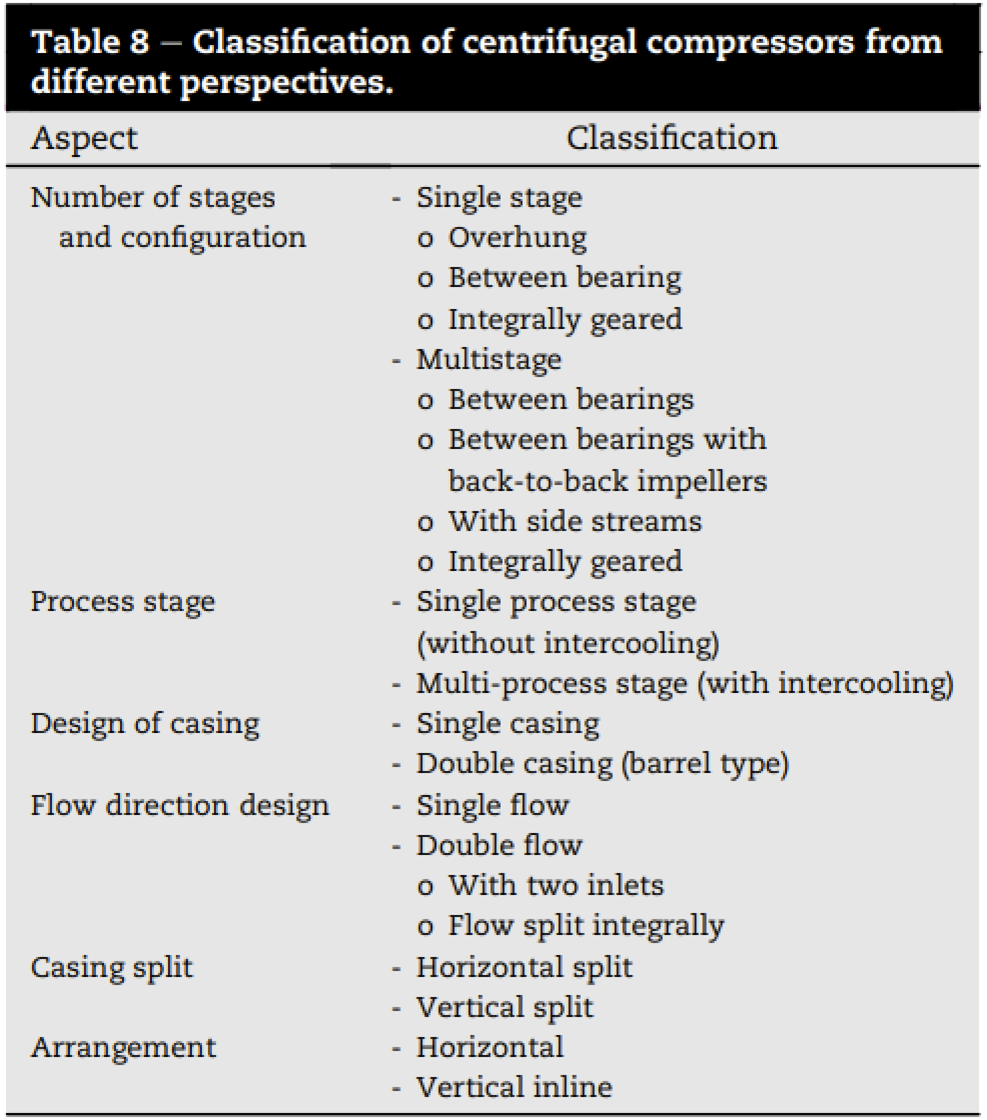

Table 8 – Classification of centrifugal compressors from different perspectives.

Aspect	Classification
Number of stages and configuration	- Single stage o Overhung o Between bearing o Integrally geared - Multistage o Between bearings o Between bearings with back-to-back impellers o With side streams o Integrally geared
Process stage	- Single process stage (without intercooling) - Multi-process stage (with intercooling)
Design of casing	- Single casing - Double casing (barrel type)
Flow direction design	- Single flow - Double flow o With two inlets o Flow split integrally
Casing split	- Horizontal split - Vertical split
Arrangement	- Horizontal - Vertical inline

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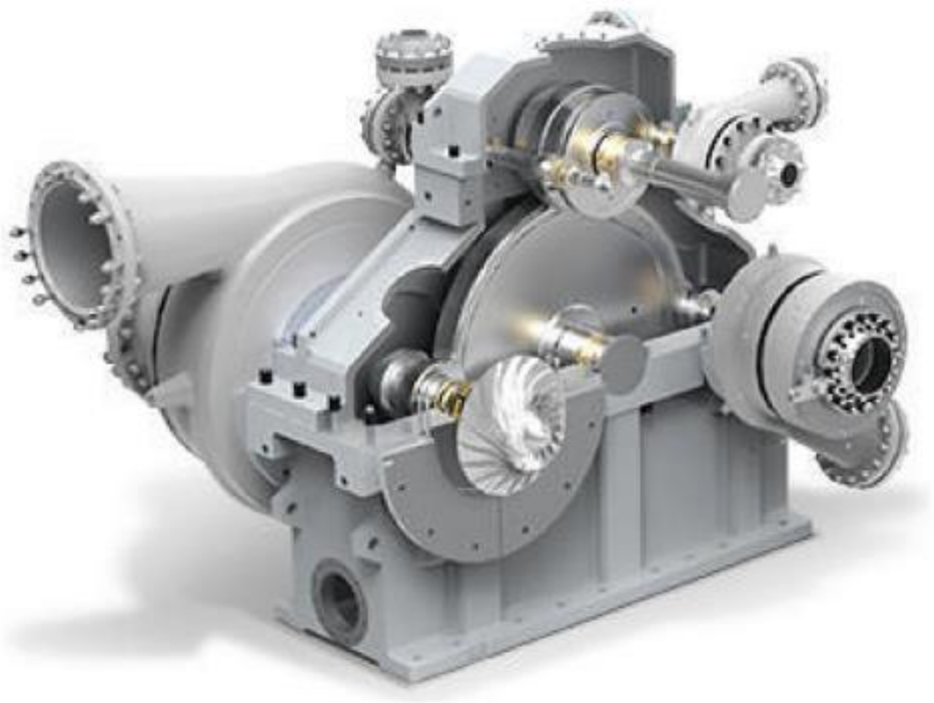

Fig. 14 – Integrally geared centrifugal compressors, courtesy of Howden

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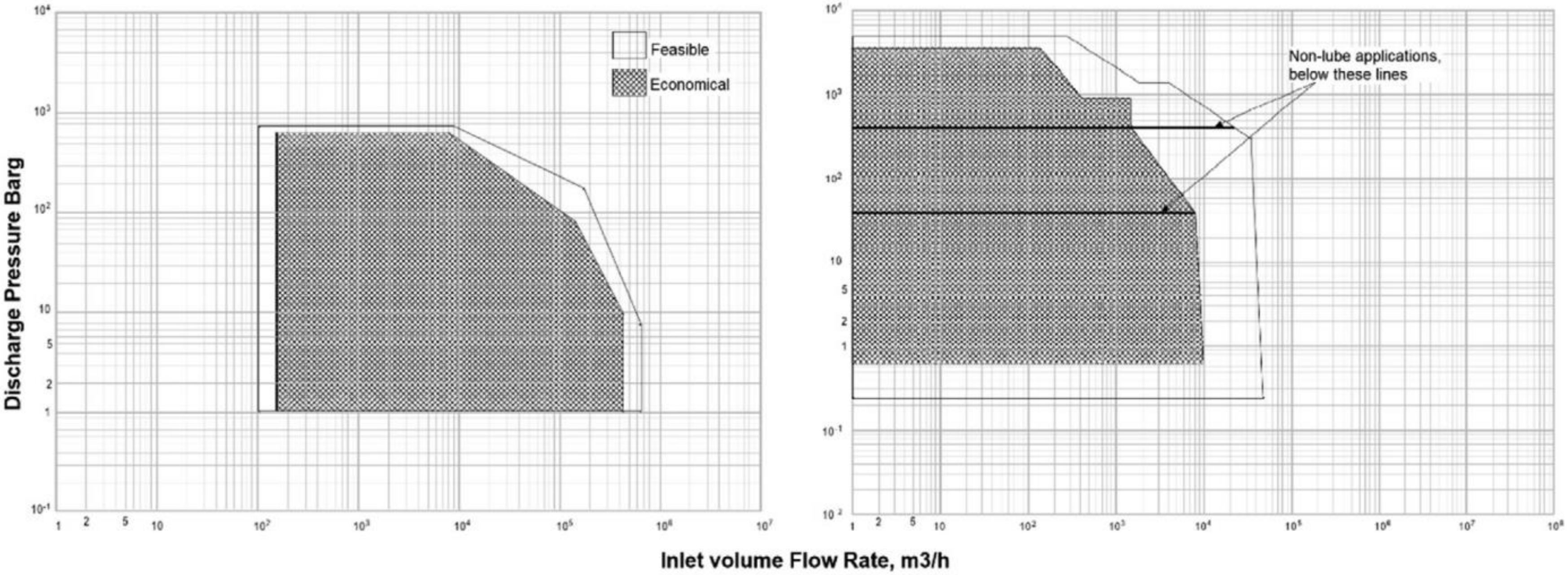

Fig. 15 – Centrifugal and reciprocating compressor application range chart [70].

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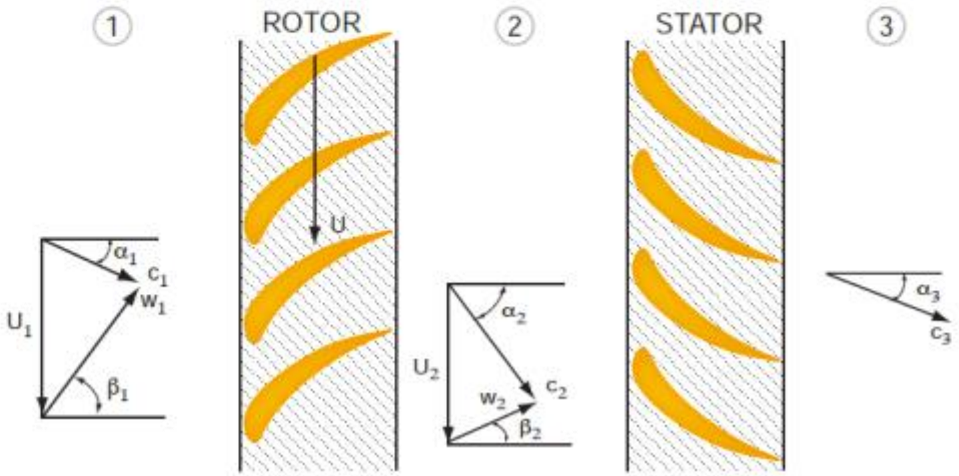
Radial and axial compressor

- Light gas compression
  - Low pressure ratio
  - Many stages (mechanical/rotordynamic) or high speed (high stress, novel materials)
  - Equation of state
- Sealing
  - Dynamic (seal leakage, scavenging)
  - Static (soft component hydrogen permeability and decompression bubbling)
- Materials and coatings
  - Hydrogen embrittlement (material loses ductility due to H_2 penetration)
  - Coating loss and disbonding
- Safety
  - Explosivity, wide flammability range, dispersion and impact radius, leak detection

Radial and axial compressor



Efficiency is not significantly affected.

Head: $$H = h_2 - h_1 = \frac{P}{W} = \omega \cdot (r_2 c_{u,2} - r_1 c_{u,1})$$

Power: $$P = \omega \cdot \Delta\tau = \omega \cdot W \cdot \Delta(r \cdot c_u) = \omega \cdot W \cdot (r_2 c_{u,2} - r_1 c_{u,1})$$

P Ratio: $$\frac{P_2}{P_1} = \left(1 + \frac{\eta}{c_p \cdot T_1} \cdot H\right)^{\frac{\gamma}{\gamma - 1}}$$

Specific Heat:
Natural gas – 2.3 kJ/kgK
Hydrogen – 14.3 kJ/kgK

Radial and axial compressor

- For the same geometry, speed, and number of stages for a hydrogen versus natural compressor, the hydrogen compressor produces similar head but significantly lower pressure ratio.
- To reach a desired pressure ratio, significantly more head is required and thus more power is required.
- To achieve desired higher head and higher pressure ratio, one can:
  - Increase the rotational speed
  - Increase the impeller diameter
  - Increase number of compression stages
- Material yield strength is limited to 120 ksi (827MPa) per API to avoid hydrogen embrittlement. This limits the impeller speed and diameter.

Pure hydrogen compression requires either:

- **Large number of compression stages**
- **High tip speed impellers**

Hydrogen coatings

- Prevent and limit hydrogen embrittlement
- Improve erosion and corrosion resistance
- Anti-fouling

… but all coatings will eventually be worn away, spalled, or dis-bonded.

Cannot be used to increase material yield strength limits for long term service applications.