SNS COLLEGE OF TECHNOLOGY
AN AUTONOMOUS INSTITUTION

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DEPARTMENT OF AGRICULTURAL ENGINEERING

COURSE CODE & NAME: 19AGT301 & HEAT POWER ENGINEERING

III YEAR / V SEMESTER

UNIT : IV IC ENGINE PERFORMANCE AND AIR COMPRESSORS

TOPIC 7 :Multi Stage Compressors

Reciprocating Compressor – Multistage

High Pressure required by Single – Stage :

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1. Requires heavy working parts.
2. Has to accommodate high pressure ratios.
3. Increased balancing problems.
4. High Torque fluctuations.
5. Requires heavy Flywheel installations.

This demands for MULTI – STAGING…!!

Why multistage compressor?

- High temp rise leads into limitation for the maximum achievable pressure rise.

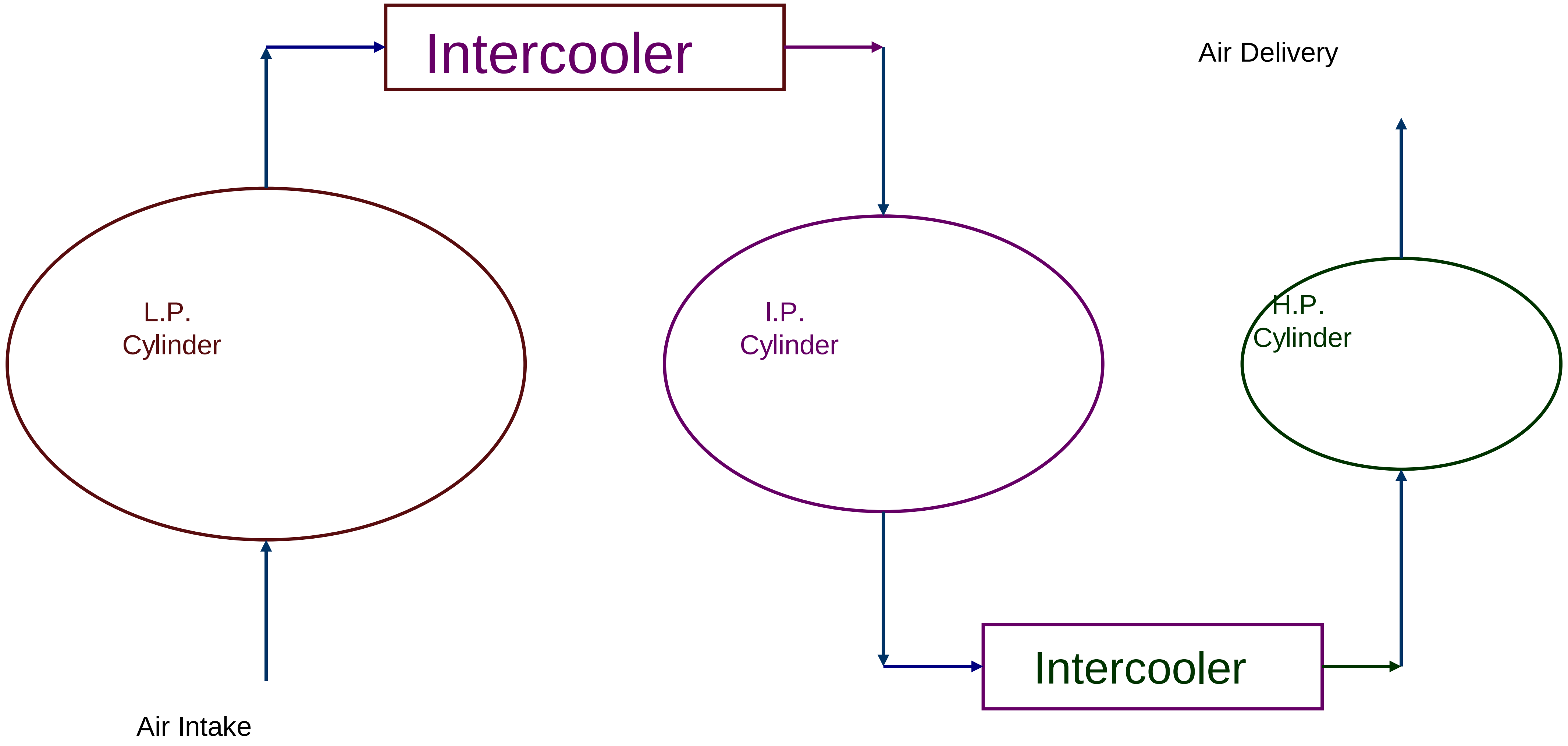
- Discharge temperature shall not exceed 150ºC and should not exceed 135^0C for hydrogen rich services

- A multistage compressor compresses air to the required pressure in multiple stages.

- Intercoolers are used in between each stage to removes heat and decrease the temperature of gas so that gas could be compressed to higher pressure without much rise in temperature

Reciprocating Compressor – Multistage

Series arrangement of cylinders, in which the compressed air from earlier cylinder (i.e. *discharge*) becomes the intake air for the next cylinder (i.e. *inlet*).



L.P. = Low Pressure

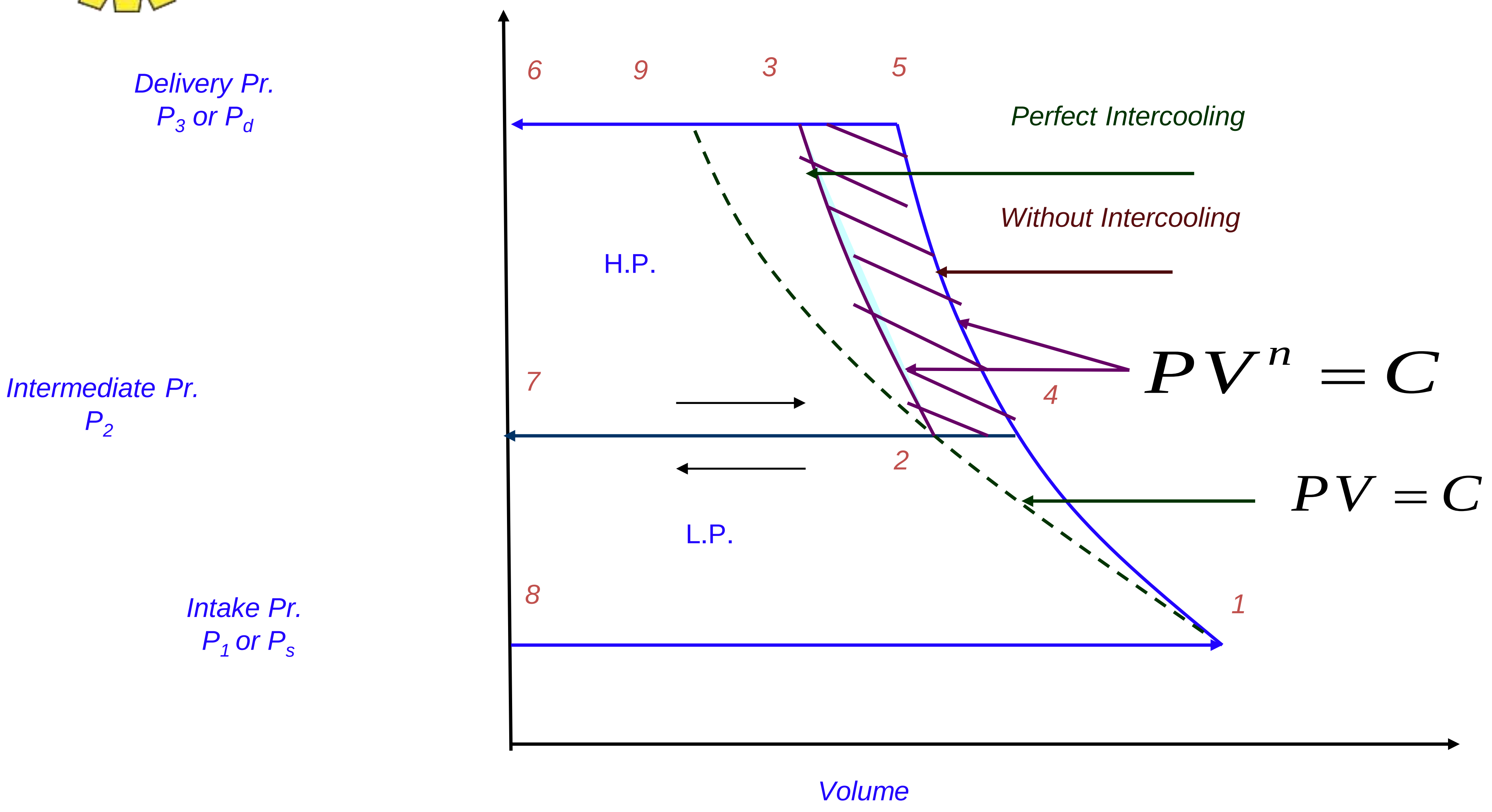
I.P. = Intermediate Pressure

H.P. = High Pressure

Intercooler :

Compressed air is *cooled* between cylinders.

Reciprocating Compressor – Multistage



Overall Pr. Range : $P_1 – P_3$

Single – stage cycle : 8-1-5-6

Without Intercooling :
L.P. : 8-1-4-7
H.P. : 7-4-5-6

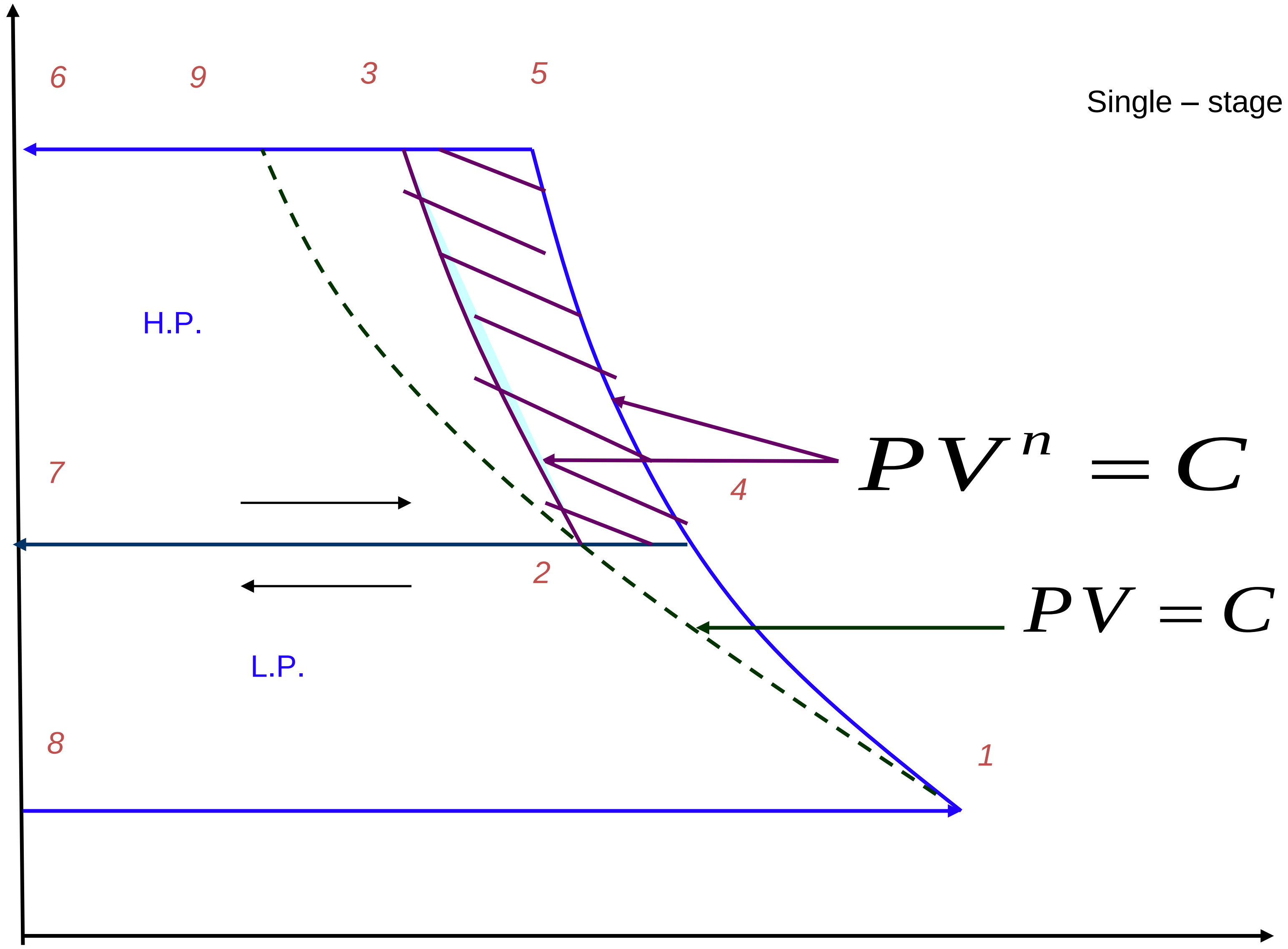
With Intercooling :
L.P. : 8-1-4-7
H.P. : 7-2-3-6

Perfect Intercooling : After initial compression in L.P. cylinder, air is cooled in the Intercooler to its original temperature, before entering H.P. cylinder
i.e. $T_2 = T_1$ OR
Points 1 and 2 are on SAME Isothermal line.

Reciprocating Compressor – Multistage

Ideal Conditions for Multi – Stage Compressors :

A. Single – Stage Compressor :



$PV^n = C$

$PV = C$

Single – stage cycle : 8-1-5-6

$$W = \frac{n}{n-1} P_1 V_1 \left[1 - \left(\frac{P_5}{P_1} \right)^{\frac{n}{n-1}} \right]$$

Delivery Temperature,

$$T_5 = T_1 \left(\frac{P_5}{P_1} \right)^{\frac{n-1}{n}}$$

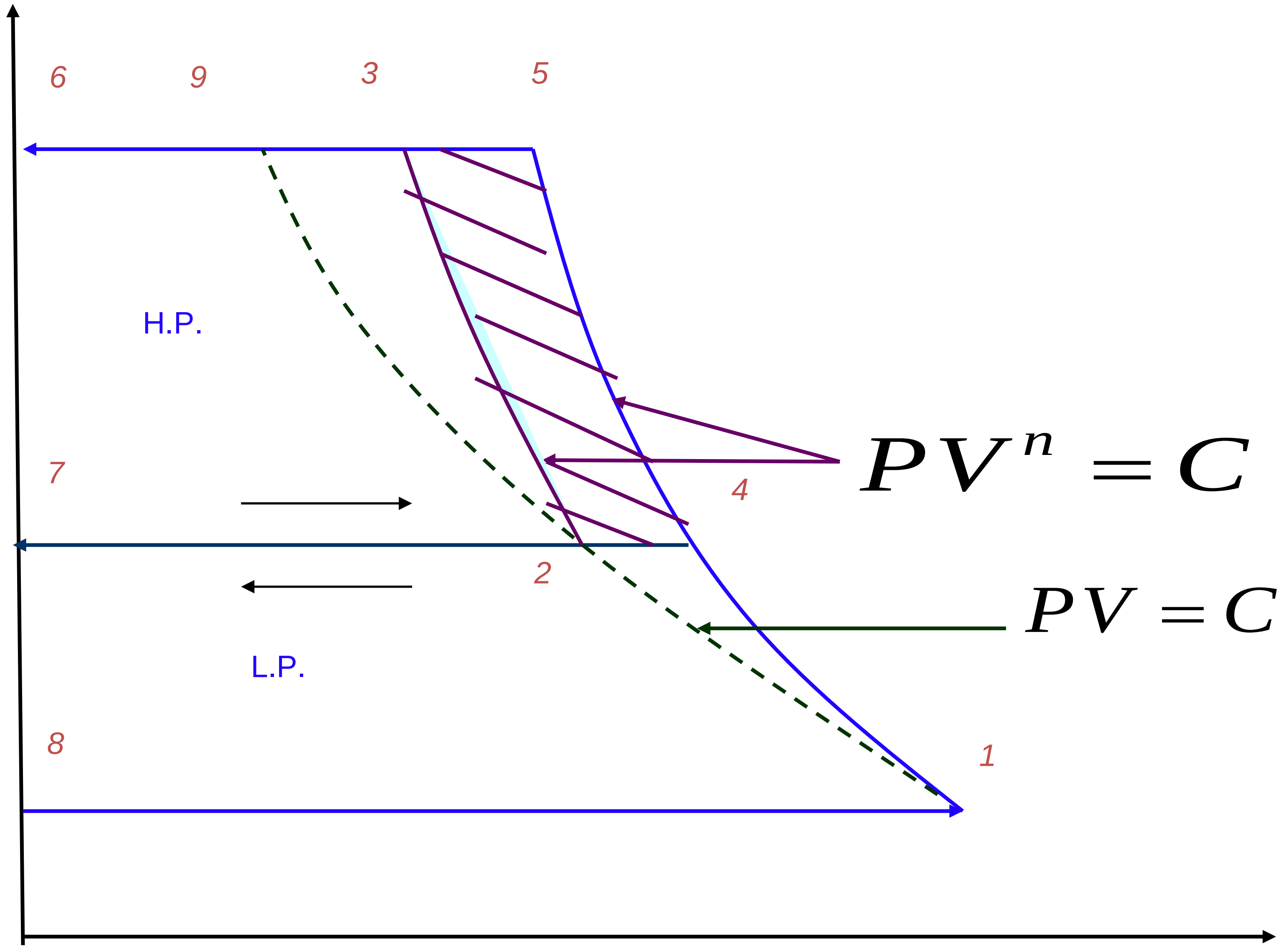
Reciprocating Compressor – Multistage

B. Two – Stage Compressor *(Without Intercooling)* :

Without Intercooling :

L.P. : 8-1-4-7

H.P. : 7-4-5-6



$$W = \frac{n}{n-1} P_1 V_1 \left[1 - \left(\frac{P_4}{P_1} \right)^{\frac{n-1}{n}} \right] + \frac{n}{n-1} P_4 V_4 \left[1 - \left(\frac{P_5}{P_4} \right)^{\frac{n-1}{n}} \right]$$

Without Intercooling $\Longrightarrow$

This is SAME as that of Work done in Single – Stage.

Delivery Temperature also remains SAME.

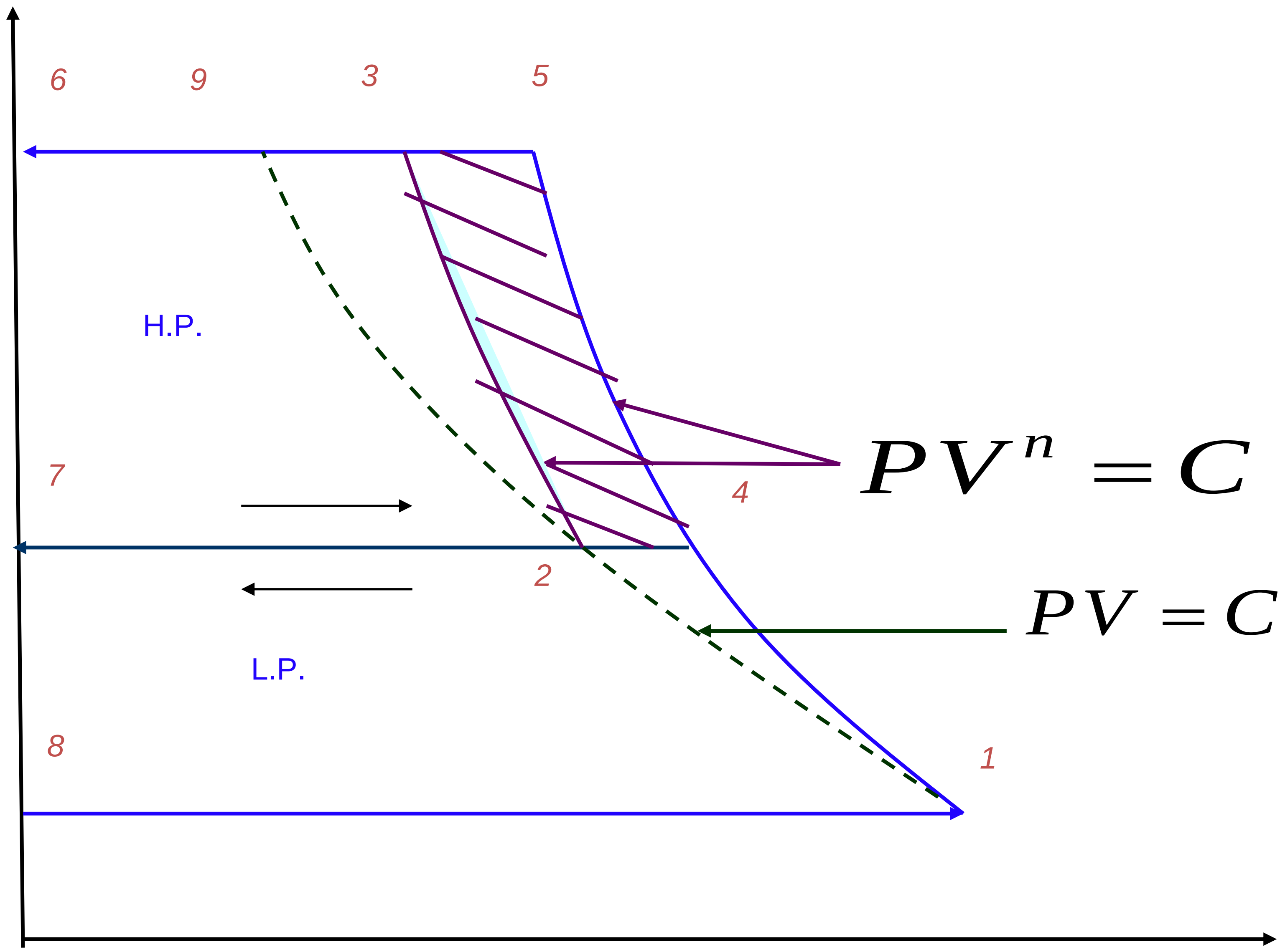
Reciprocating Compressor – Multistage

C. Two – Stage Compressor *(With Perfect Intercooling)* :

With Intercooling :

L.P. : 8-1-4-7-8

H.P. : 7-2-3-6-7



$PV^n = C$

$PV = C$

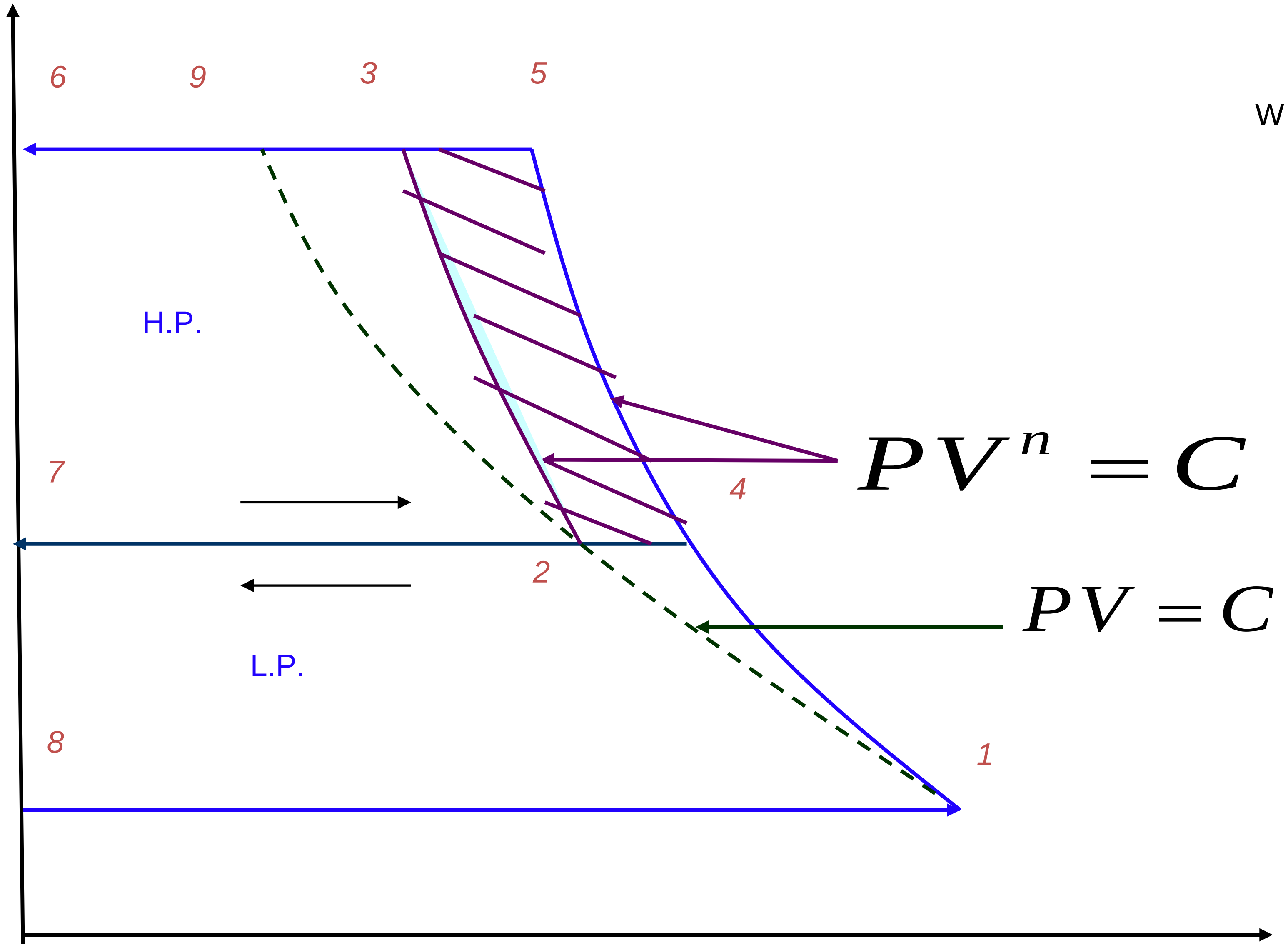
$$W = \frac{n}{n-1} P_1 V_1 \left[1 - \left(\frac{P_4}{P_1} \right)^{\frac{n-1}{n}} \right] + \frac{n}{n-1} P_2 V_2 \left[1 - \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} \right]$$

Delivery Temperature,

$$T_3 = T_2 \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} = T_1 \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}}, \quad as\, T_2 = T_1$$

Reciprocating Compressor – Multistage

C. Two – Stage Compressor *(With Perfect Intercooling)* :



$$PV^n = C$$

$$PV = C$$

With Intercooling :

L.P. : 8-1-4-7-8

H.P. : 7-2-3-6-7

Now, $T_2 = T_1$

$P_2V_2 = P_1V_1$

Also $P_4 = P_2$

$$W = \frac{n}{n-1} P_1 V_1 \left[2 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} \right]$$

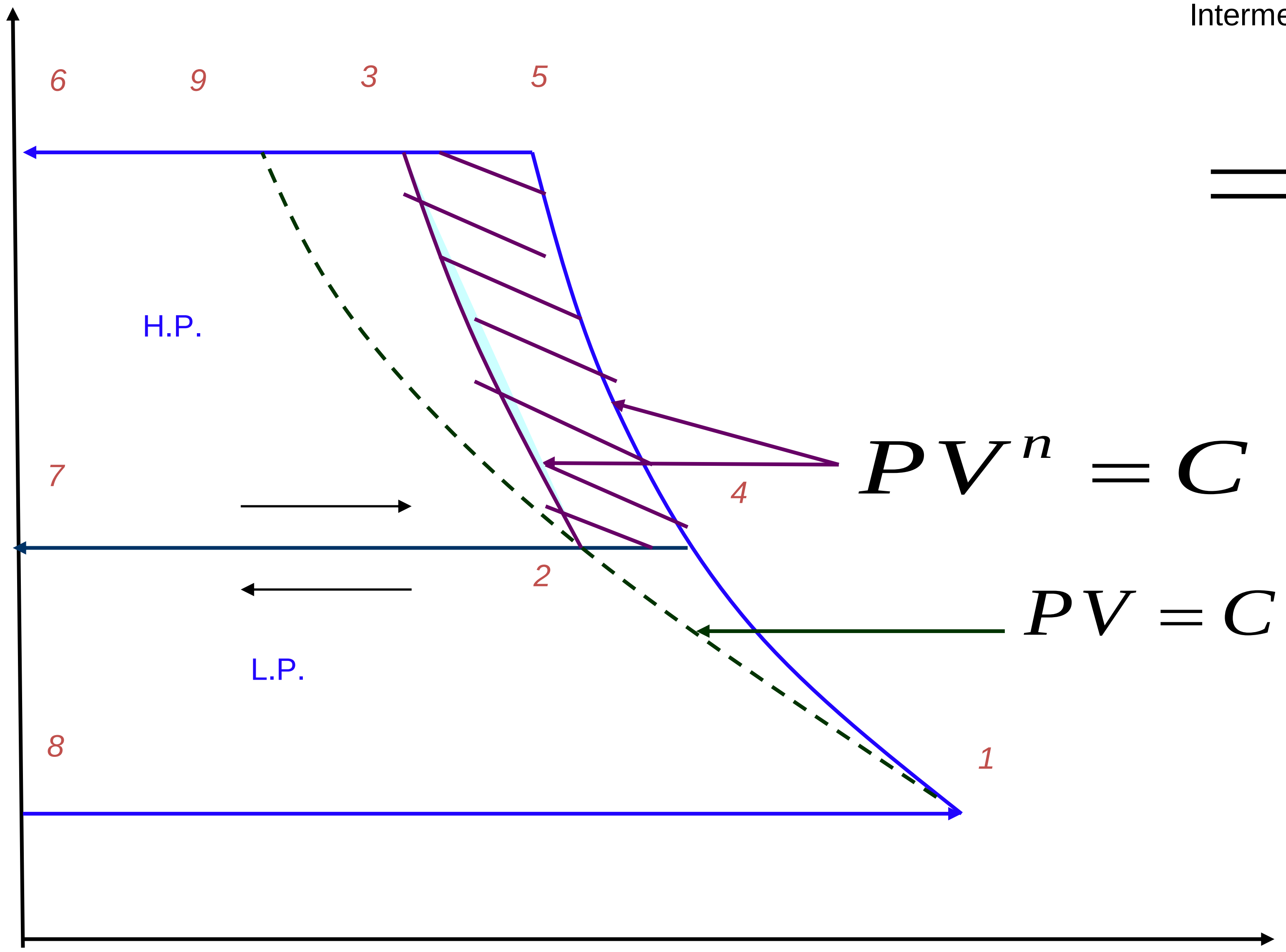
Shaded Area 2-4-5-3-2 : Work Saving due to Intercooler…!!

Reciprocating Compressor – Multistage

Condition for Min. Work :

Intermediate Pr. $P_2 \rightarrow P_1$: Area 2-4-5-3-2 → 0

Intermediate Pr. $P_2 \rightarrow P_3$: Area 2-4-5-3-2 → 0



$\Longrightarrow$ There is an *Optimum* P_2 for which Area 2-4-5-3-2 is maximum,
i.e. Work is minimum…!!

$$W = \frac{n}{n-1} P_1 V_1 \left[2 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} \right]$$

For min. Work,

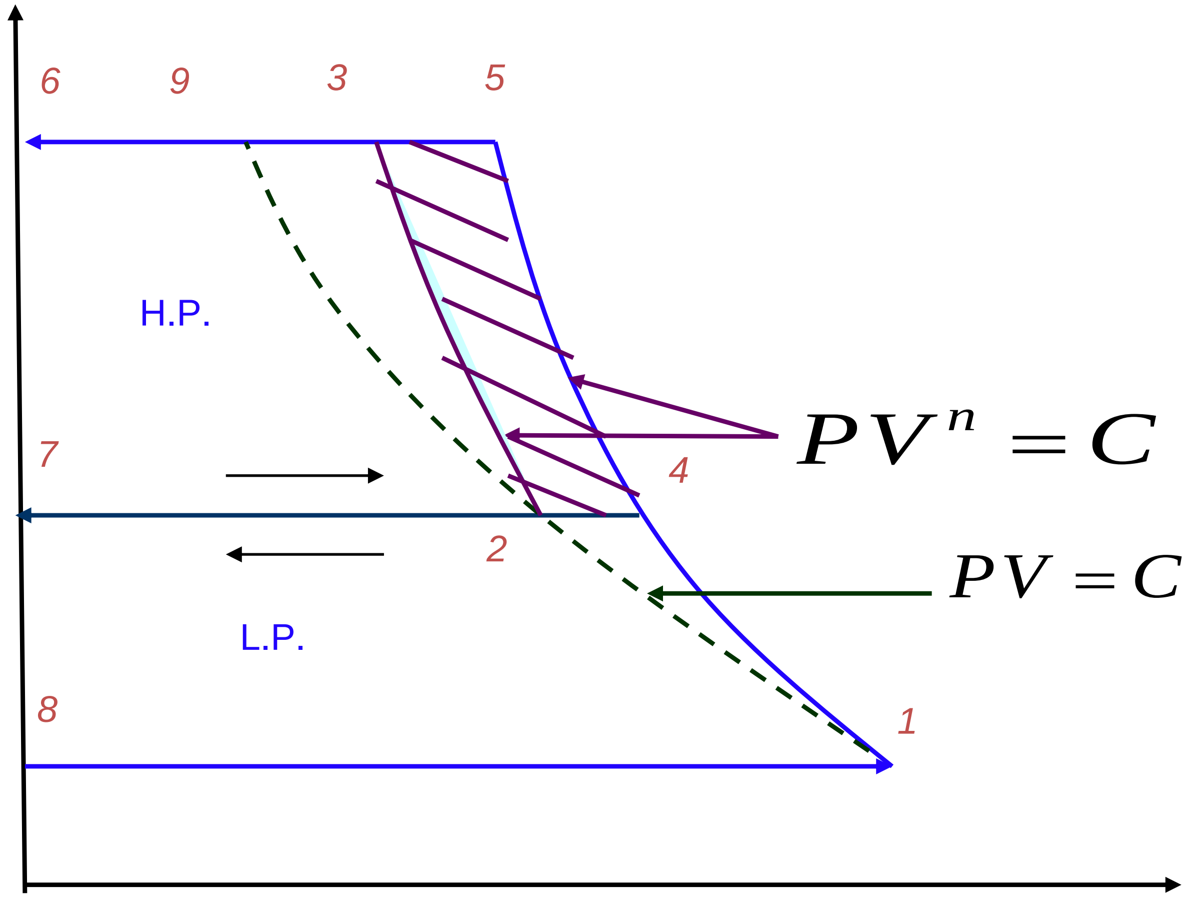
$$\frac{dW}{dP_2} = \frac{d\left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} \right]}{dP_2} = 0$$

Reciprocating Compressor – Multistage

Condition for Min. Work :

$$\frac{dW}{dP_2} = \frac{d\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}}\right]}{dP_2} = 0$$

$$\frac{1}{(P_1)^{\frac{n-1}{n}}} \bullet \left(\frac{n-1}{n}\right)(P_2)^{\left(\frac{n-1}{n}\right)-1} + (P_3)^{\left(\frac{n-1}{n}\right)} \bullet \left[-\left(\frac{n-1}{n}\right)(P_2)^{\left(-\frac{n-1}{n}\right)-1}\right] = 0$$



$$\frac{(P_2)^{-1/n}}{(P_2)^{\left(\frac{-2n+1}{n}\right)}} = (P_1 P_3)^{\left(\frac{n-1}{n}\right)}$$

$$(P_2)^2 = (P_1 P_3)$$

$$\boxed{P_2 = \sqrt{P_1 P_3} \quad OR \quad \frac{P_2}{P_1} = \frac{P_3}{P_2}}$$

Reciprocating Compressor – Multistage

P_2 obtained with this condition (Pr. Ratio per stage is equal) is the Ideal Intermediate Pr. Which, with Perfect Intercooling, gives Minimum Work, W_{min}.

$\Rightarrow$ Equal Work per cylinder…!!

$$W = \frac{2n}{n-1} P_1 V_1 \left[1 - \left(\frac{(P_1 P_3)^{1/2}}{P_1} \right)^{\frac{n-1}{n}} \right]$$

$$W = \frac{2n}{n-1} P_1 V_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right]$$

$$\boxed{W = \frac{2n}{n-1} P_1 V_1 \left[1 - \left(\frac{P_3}{P_1} \right)^{\frac{n-1}{2n}} \right]}$$

Reciprocating Compressor – Efficiency

Isothermal work done / cycle = Area of *P* – *V* Diagram

$$= P_1V_1 \log_e(P_2/P_1)$$

$$\text{Isothermal Power} = \frac{P_1V_1 \log_e(P_2/P_1)\, N}{60 \text{ X } 1000} \text{ kW}$$

Indicated Power : Power obtained from the actual indicator card taken during a test on the compressor.

$$\text{Compressor Efficiency} = \frac{\text{Isothermal Power}}{\text{Indicated Power}}$$

$$\text{Isothermal Efficiency} = \frac{\text{Isothermal Power}}{\text{Shaft Power}}$$

NOTE : Shaft Power = Brake Power required to drive the Compressor.

Reciprocating Compressor – Efficiency

Adiabatic Efficiency : Ratio of Power required to drive the Compressor; compared with the area of the hypothetical Indicator Diagram; assuming Adiabatic Compression.

$$\eta_{adiabatic} = \frac{\frac{\gamma}{\gamma-1} P_1 V_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \right]}{Brake\ Power\ required\ to\ drive\ the\ Compressor}$$

Mechanical Efficiency : Ratio of mechanical output to mechanical input.

Mechanical Efficiency, $\eta_{mech} = \dfrac{\text{Indicated Power}}{\text{Shaft Power}}$

Reciprocating Compressor – Efficiency

How to Increase Isothermal Efficiency ?

A. Spray Injection : Assimilation of water into the compressor cylinder towards the compression stroke.

Object is to cool the air for next operation.

Demerits : 1. Requires *special gear* for injection.

2. Injected water interferes with the *cylinder lubrication*.

3. Damage to *cylinder walls* and *valves*.

4. Water must be separated before delivery of air.

B. Water Jacketing : Circulating water around the cylinder to help for cooling the air during compression.

Reciprocating Compressor – Efficiency

How to Increase Isothermal Efficiency ?

C. Inter – Cooling : For high speed and high Pr. Ratio compressors.

Compressed air from earlier stage is cooled to its original temperature before passing it to the next stage.

D. External Fins : For small capacity compressors, fins on external surfaces are useful.

E. Cylinder Proportions : Short stroke and large bore provides much greater surface for cooling.

Cylinder head surface is far more effective than barrel surface.

Reciprocating Compressor – Efficiency

Clearance Volume : Consists of *two* spaces.

1. Space between cylinder end & the piston to allow for wear.
2. Space for reception of valves.

High – class H.P. compressors : Clearance Vol. = 3 % of Swept Vol.
: Lead (Pb) fuse wire used to measure the gap between cylinder end and piston.

Low – grade L.P. compressors : Clearance Vol. = 6 % of Swept Vol.
: Flattened ball of putty used to measure the gap between cylinder end and piston.

Effect of Clearance Vol. :

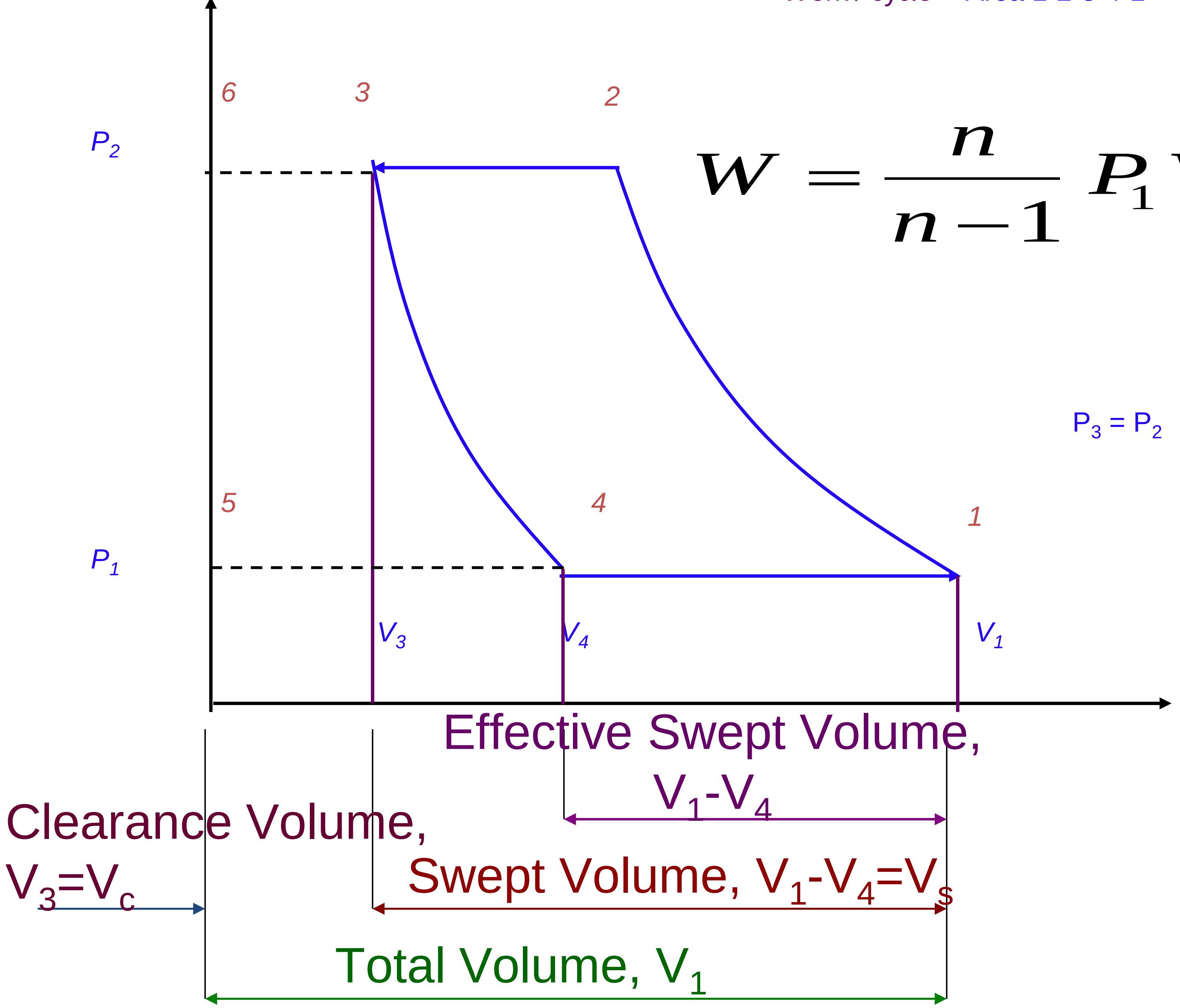
Vol. taken in per stroke < Swept Vol. ↑ Size of compressor ⟹

↑ Power to drive compressor.

Reciprocating Compressor – Work Done

Assumption : Compression and Expansion follow same Law.

Work / cycle = Area 1-2-3-4-1



Effective Swept Volume, V_1-V_4

Clearance Volume, V_3=V_c

Swept Volume, V_1-V_4=V_s

Total Volume, V_1

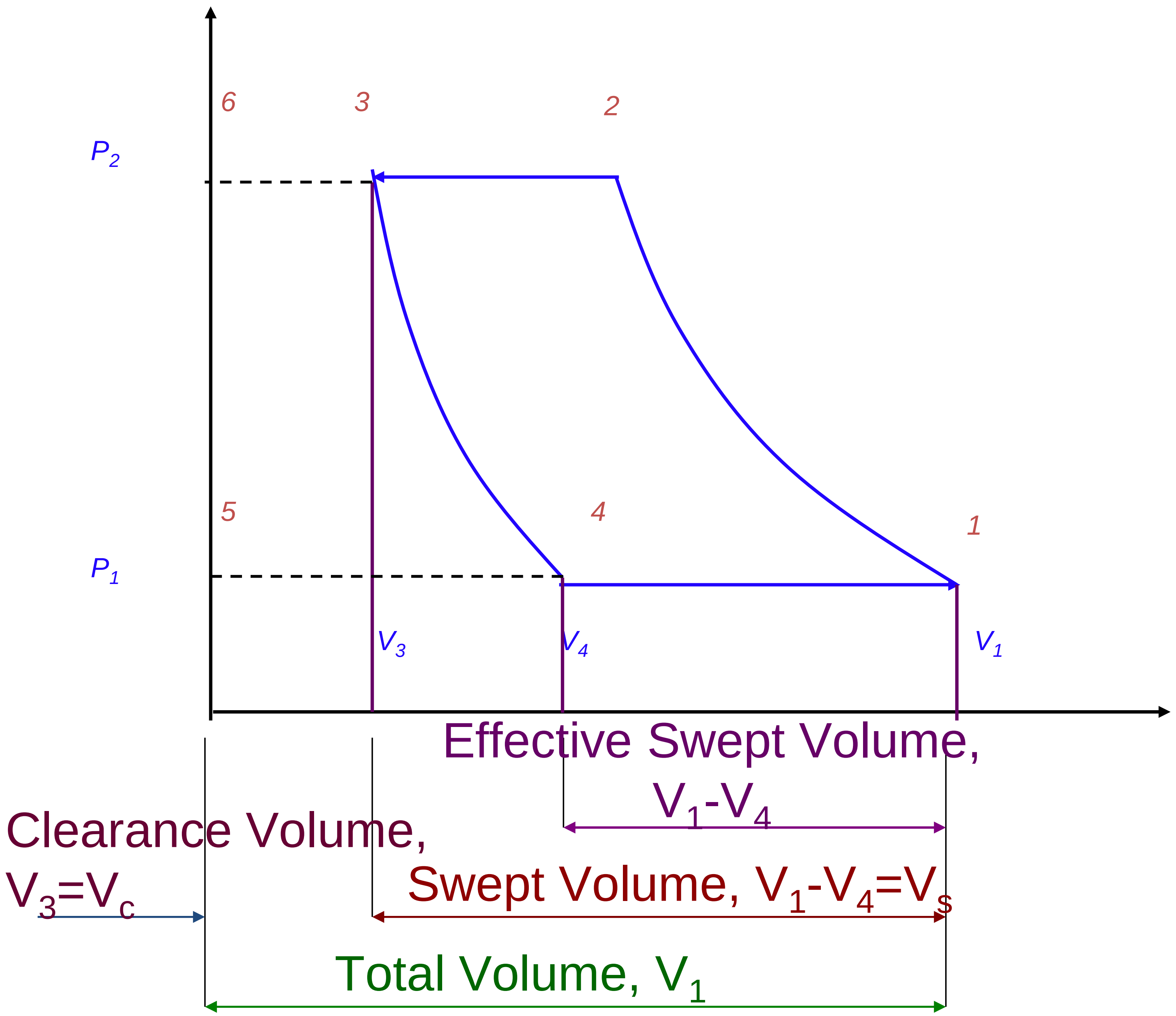
$$W = \frac{n}{n-1} P_1 V_1 \left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right] - \frac{n}{n-1} P_4 V_4 \left[1-\left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}}\right]$$

$P_3 = P_2$ and $P_4 = P_1$

$$W = \frac{n}{n-1} P_1 (V_1 - V_4) \left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]$$

$$= \frac{n}{n-1} P_1 V_a \left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]$$

Reciprocating Compressor – Work Done



$$W = \frac{n}{n-1} m_1 R T_1 \left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]$$

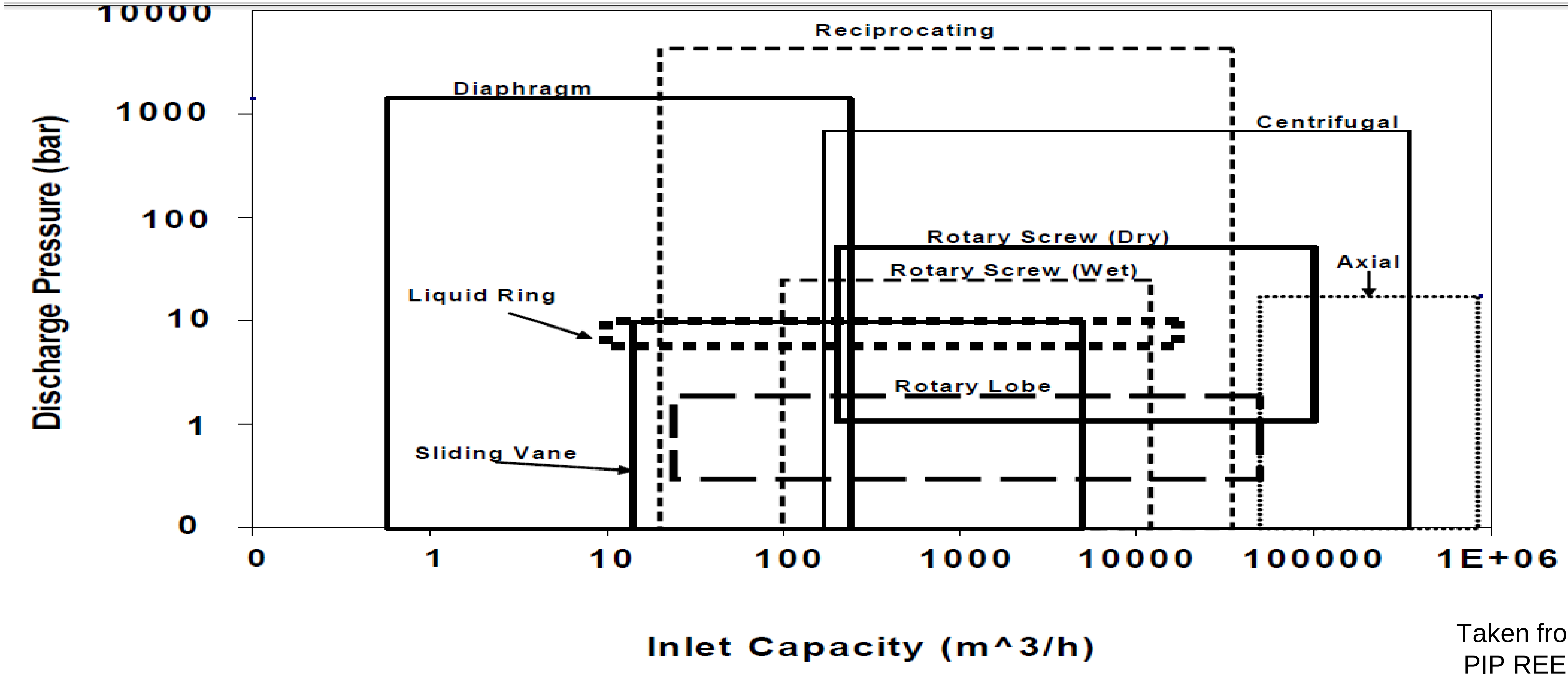
m_1 is the actual mass of air delivered.

Work done / kg of air delivered :

$$W = \frac{n}{n-1} R T_1 \left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]$$

How to select a particular type of compressor ?

Graph showing operating regions of various compressors



Taken from
PIP REEC001
Compressor Selection
Guidelines

Table showing operating conditions of various compressors

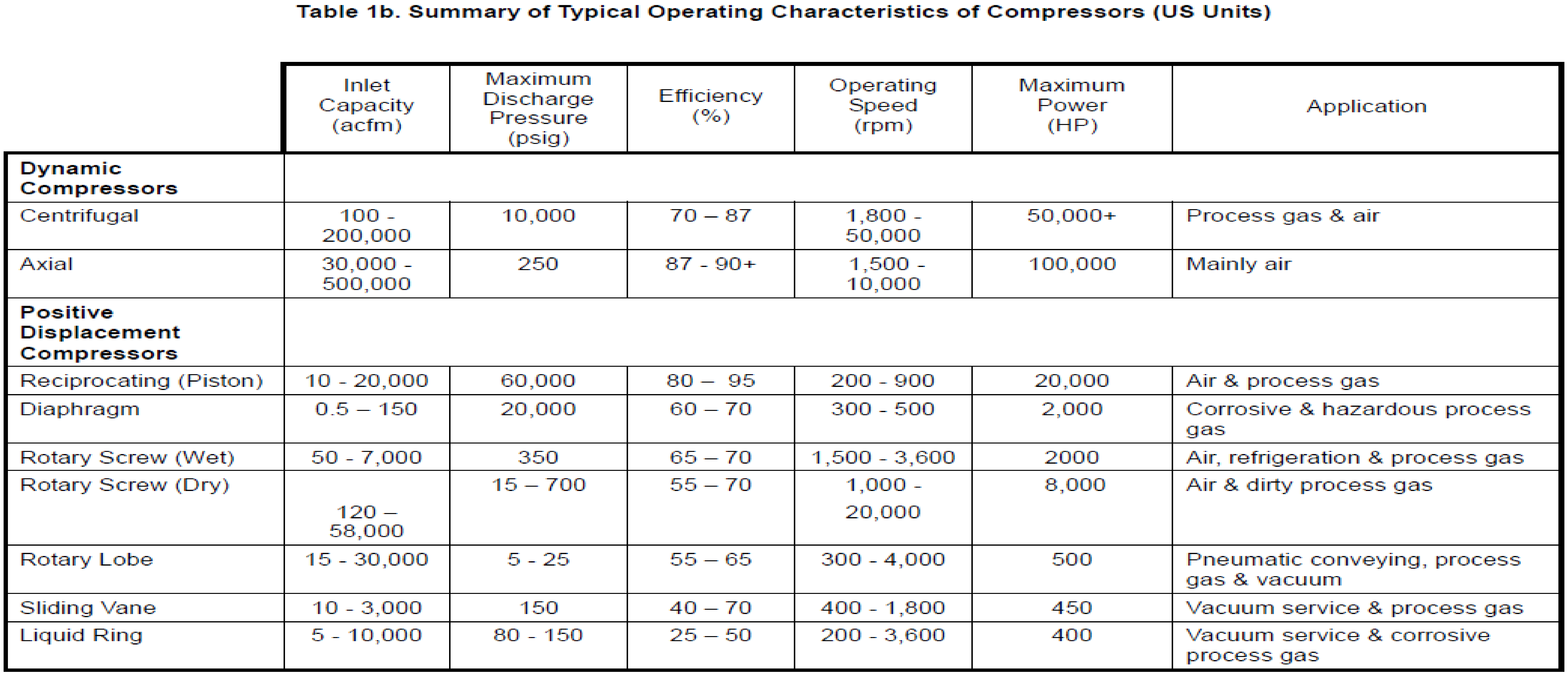


Table 1b. Summary of Typical Operating Characteristics of Compressors (US Units)

	Inlet Capacity (acfm)	Maximum Discharge Pressure (psig)	Efficiency (%)	Operating Speed (rpm)	Maximum Power (HP)	Application
Dynamic Compressors						
Centrifugal	100 - 200,000	10,000	70 – 87	1,800 - 50,000	50,000+	Process gas & air
Axial	30,000 - 500,000	250	87 - 90+	1,500 - 10,000	100,000	Mainly air
Positive Displacement Compressors						
Reciprocating (Piston)	10 - 20,000	60,000	80 – 95	200 - 900	20,000	Air & process gas
Diaphragm	0.5 – 150	20,000	60 – 70	300 - 500	2,000	Corrosive & hazardous process gas
Rotary Screw (Wet)	50 - 7,000	350	65 – 70	1,500 - 3,600	2000	Air, refrigeration & process gas
Rotary Screw (Dry)	120 – 58,000	15 – 700	55 – 70	1,000 - 20,000	8,000	Air & dirty process gas
Rotary Lobe	15 - 30,000	5 - 25	55 – 65	300 - 4,000	500	Pneumatic conveying, process gas & vacuum
Sliding Vane	10 - 3,000	150	40 – 70	400 - 1,800	450	Vacuum service & process gas
Liquid Ring	5 - 10,000	80 - 150	25 – 50	200 - 3,600	400	Vacuum service & corrosive process gas

Taken from
PIP REEC001
Compressor Selection Guidelines

Advantages and Disadvantages of Dynamic compressors

	Advantages	Disadvantages
Dynamic Compressors		
Centrifugal	•Wide operating range •High reliability •Low Maintenance	•Instability at reduced flow •Sensitive to gas composition change
Axial	•High Capacity for given size •High efficiency •Heavy duty •Low maintenance	•Low Compression ratios •Limited turndown

Advantages and Disadvantages of Positive displacement compressors

	Advantages	**Disadvantages**
Positive displacement compressor		
Reciprocating	•Wide pressure ratios •High efficiency	•Heavy foundation required •Flow pulsation •High maintenance
Diaphragm	•Very high pressure •Low flow •No moving seal	•Limited capacity range •Periodic replacement of diaphragm
Screw	•Wide application •High efficiency •High pressure ratio	•Expensive •Unsuitable for corrosive or dirty gases

Thank You